NEW RESEARCH: Strange galaxies found lacking dark matter p. 44

MARCH 2020

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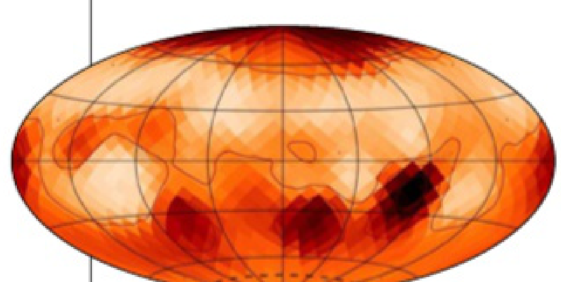
ON THE COVER

The Carina Nebula is the largest and brightest Milky Way star-forming region. Hubble captured this image of its dusty pillars.

NASA/ESA/N. SMITH (UC, BERKELEY)/ THE HUBBLE HERITAGE TEAM (STScI/AURA)

FEATURES



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Remembering Hubble

The so-called Pillars of Creation, towers of dust in the Eagle Nebula, became the most celebrated image ever made with HST. NASA, ESA, AND THE HUBBLE HERITAGE TEAM (STScI/AURA)

Launched in 1990, the Hubble Space Telescope became an instant fiasco in orbit. During in-orbit testing, astronomers immediately found that the 2.4-meter mirror was flawed. It had been figured incorrectly at Perkin-Elmer due to a lens in a testing instrument that was out of place by 1.3 millimeters. The world's greatest space telescope became an instant boondoggle and the butt of jokes on the late-night talk shows.

In December 1993, the first servicing mission, using the space shuttle *Endeavour*, fixed the problem with a set of corrective optics. COSTAR, the corrective optics package, was supplemented with the Wide Field and Planetary Camera 2, which also had corrective optics and allowed for a series of magnificent images to be made. All was right again with the world's greatest in-orbit telescope.

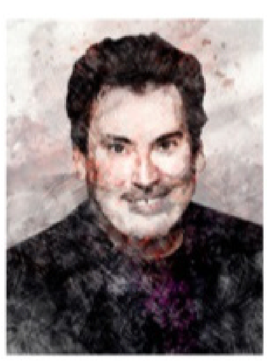
On this 30th anniversary of the launching of Hubble, Senior Editor Rich Talcott delivers a magnificently illustrated story highlighting some of the space telescope's greatest victories. Among them is ongoing research into one of the greatest mysteries of cosmology: the nature of dark energy. The fact that the universe's expansion is accelerating and we don't know the cause is somewhat astonishing, and villages full of cosmologists are working on this problem to try to understand it. Hubble played the key role in observing the distant supernovae that revealed the accelerating cosmos.

Hubble has also contributed substantially to understanding how stars form in the universe. In a series of so-called deep field exposures, beginning in 1995, the telescope has produced looks at small areas of the sky. A key result of studying these distant fields of mostly galaxies has been deciphering the rate at which stars form as a function of distance or time. This helps to reveal how galaxies themselves formed over time, and how they have evolved.

And then there are the images: Hubble has created many thousands of spectacular pictures of the cosmos, the best ever made. One of them is the so-called Pillars of Creation, towers of dust in the Eagle Nebula, a shot created by our very own Jeff Hester. But so many others are there. Enjoy the sample within this issue. It is a celebration of the greatest astronomical instrument ever made.

Yours truly,

David J. Eicher
Editor



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The official proper name for Earth's companion is "the Moon." NASA/JPL/USGS

We welcome your comments at Astronomy Letters, P.O. Box 1612, Waukesha, WI 53187; or email to **letters@astronomy.com**. *Please include your name, city, state, and country. Letters may be edited for space and clarity.*

Future astronomer

I am 12 years old and want to be an astronomer one day. I am writing because I really like the Paths of the Planets chart in the November 2019 issue of *Astronomy* magazine. It shows a lot of information about the planets and where to find them in the night sky when they are most visible. I love looking at the night sky, and this magazine gives me plenty of information I can use to find space objects, and it helps me plan for what to expect in the days ahead. That is one of my favorite things about your magazine. **— Zach Owens,** Birmingham, AL

What's in a name ...

I was really motivated to send you this letter after reading Robin Canup's article in the November 2019 issue, "The Moon's violent origin." Lately, I've realized that the Moon is so unique that we should stop calling it just another moon. It is the Earth/Moon system — a double planet. There is no other system of which I am aware in the solar system that duplicates the Moon's origin and its uniqueness. Calling it "the Moon" obscures what we have learned about it since the Apollo samples which reshaped our understanding of its relationship to Earth. **— Jim Carlisle,** Atascadero, CA

From the editors: When New Horizons zipped by the Pluto system, it revealed that a powerful past collision likely spawned Pluto's moons — including Charon, which is actually larger relative to Pluto than the Moon is to Earth. One other note: The official proper name of Earth's moon is "the Moon." Perhaps think of that as a sign of respect; it's not "just another moon," but the Moon, capital letter and all.

Concise reporting

I just want to give a big thanks to Bob Berman for finally raising a subject (in his aptly titled "The media's universe") that, quite frankly, I view as harmful to astronomy. His precise candor never fails to make me grin.

I also hope that others may take a closer look at his piece and take the time to at least learn more about this discipline to augment more concise reporting. **— C. Williams,** Green Cove Springs, FL

SNAPSHOT

A GHOSTLY SPACE FACE

A look only merging galaxies could give.

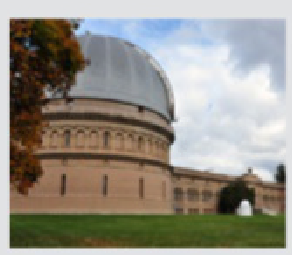
What at first appears to be a face with glowing eyes is actually a unique moment in time, captured by the Hubble Space Telescope.

Galaxies grow and evolve through collisions. Although most smash-ups aren't head-on, Arp–Madore 2026–424 apparently didn't get the memo. In June 2019, Hubble took this visible-light snapshot of the cosmic crash in progress.

The central regions, or bulges, of the galaxies glow brightly like a pair of supernatural eyes. Gas, dust, and stars in the galaxies' arms have been yanked around by gravitational effects, forming a huge, bluish ring structure that serves as the head and nose.

Cosmically speaking, ring structures like this don't last long — only about 100 million years. As the merger progresses, the face will distort into unrecognizability. And in about 1 billion to 2 billion years, the galaxies will have merged completely. –ALISON KLESMAN

HOT BYTES

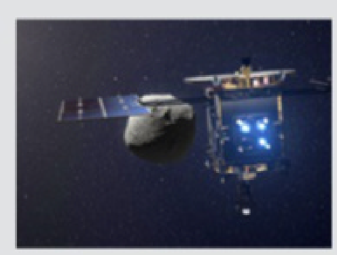


NEW LIFE

The nonprofit Yerkes Future Foundation will take ownership of Yerkes Observatory, which closed in 2018, from the University of Chicago. The foundation aims to reopen the historic observatory for public outreach and astronomical research.

SMART SPACE SUIT

A collaboration between the NASA Haughton Mars Project and several research organizations has successfully tested an astronaut smart glove that will allow explorers to wirelessly operate equipment using hand gestures.



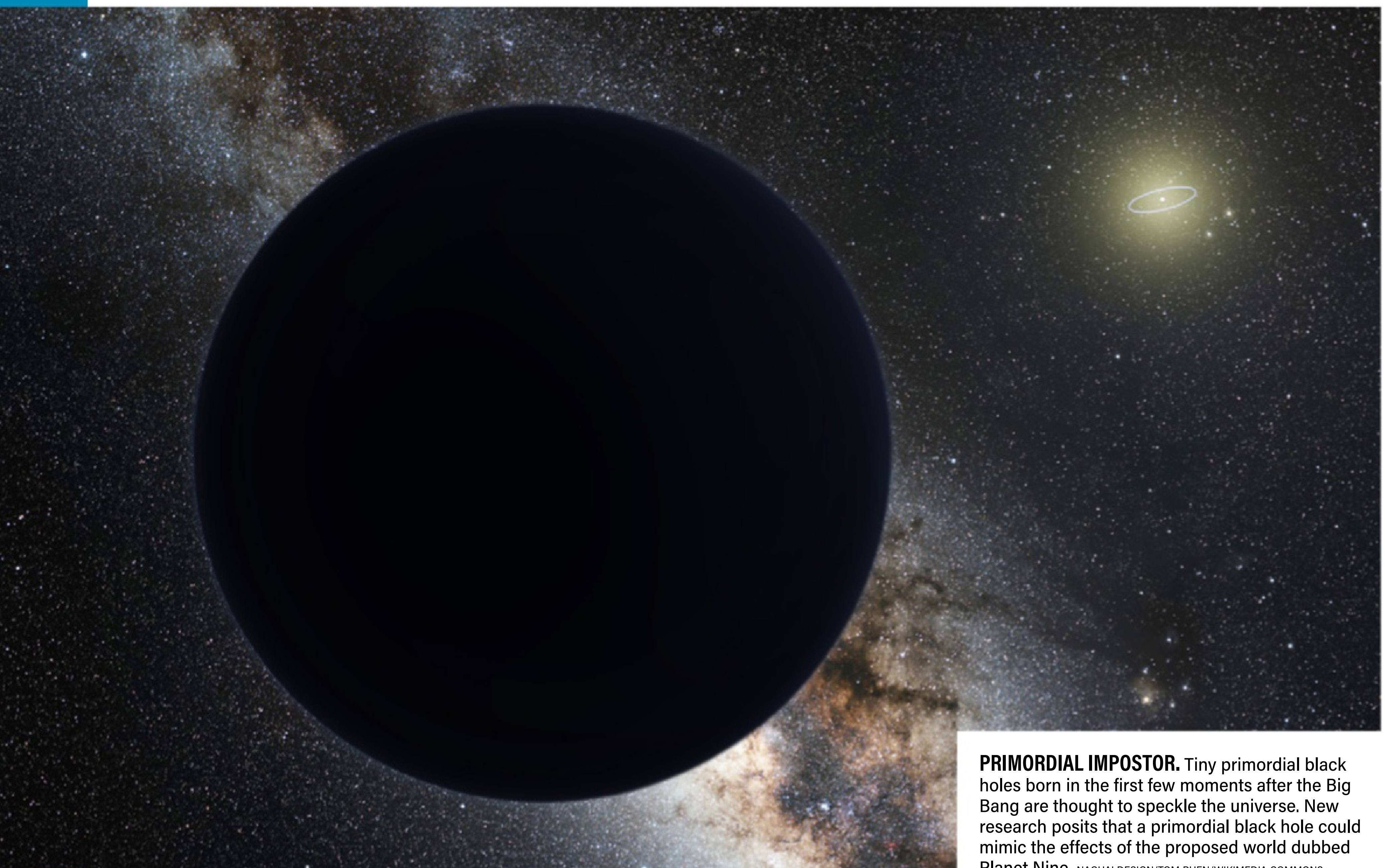
HEADED HOME

The Japan Aerospace Exploration Agency's Hayabusa2 spacecraft departed asteroid Ryugu on November 13, carrying along with it several samples from the rocky space object for closer examination by researchers back home on Earth.

NASA, ESA, J. DALCANTON, B.F. WILLIAMS, AND M. DURBIN (UNIVERSITY OF WASHINGTON). BOTTOM FROM LEFT: MUNFORD (WIKIMEDIA COMMONS); HAUGHTON-MARS PROJECT/P. LEE; DLR GERMAN AEROSPACE CENTER

IS PLANET NINE A TINY BLACK HOLE?

Oddly orbiting objects hint at a massive planet in the outer solar system. But some researchers think a black hole could fit the bill.



PRIMORDIAL IMPOSTOR. Tiny primordial black holes born in the first few moments after the Big Bang are thought to speckle the universe. New research posits that a primordial black hole could mimic the effects of the proposed world dubbed Planet Nine. NAGUALDESIGN/TOM RUEN/WIKIMEDIA COMMONS

The strange orbits of distant space rocks suggest there's a 5- to 15-Earth-mass world dubbed Planet Nine lurking in the outskirts of the solar system. But now, a team of scientists is proposing something far stranger may be influencing the orbits of these distant bodies: a primordial black hole.

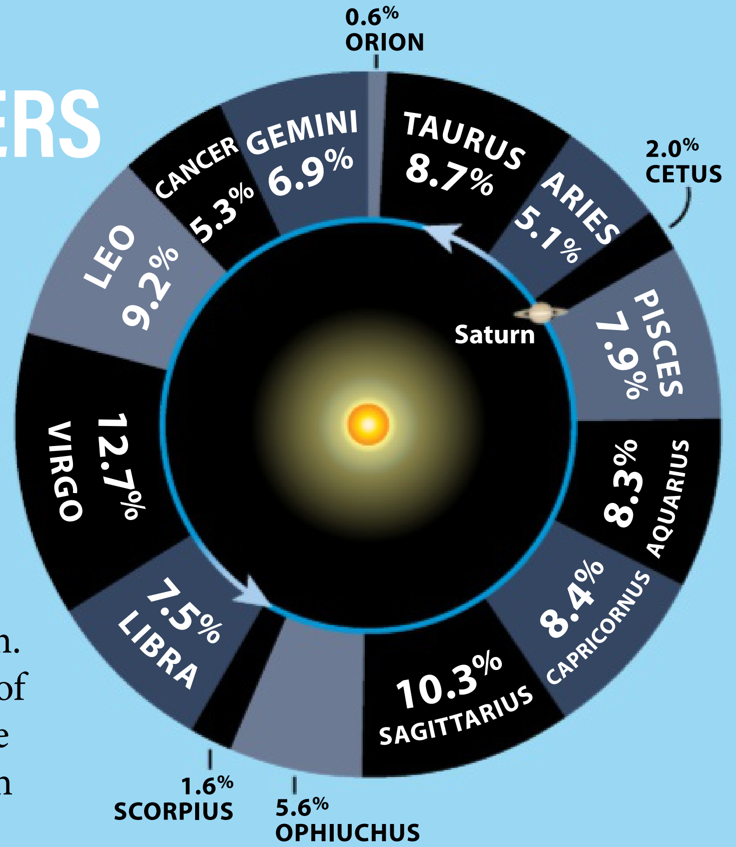
Primordial black holes are believed to have popped into existence within the first few fractions of a second after the Big Bang. Their existence has yet to be confirmed. But, according to research posted September 24 to the preprint site arXiv, if primordial black holes exist, there's no reason the solar system couldn't have captured one whose gravity would mimic the effects of the proposed Planet Nine. And because black holes are incredibly adept at crushing down matter, the black hole equivalent to 5 Earth masses would be only slightly bigger than a baseball.

As part of the Optical Gravitational Lensing Experiment (OGLE), astronomers have spent almost three decades monitoring the sky in search of gravitational microlensing events, which occur when a massive foreground object (such as a planet or tiny black hole) passes directly in front of a background object (such as a star). If the alignment of the objects is perfect, the foreground object acts as a sort of lens, distorting and amplifying the light from the object behind it.

After digging through five years of OGLE observations, researchers uncovered six microlensing events that seem to have occurred when objects roughly 0.5 to 20 Earth masses acted as gravitational lenses. These lensing objects, located about 26,000 light-years away toward the Milky Way's galactic bulge, could correspond to free-floating

THE RINGED WORLD WANDERS

A ZODIACAL JOURNEY. Saturn takes 29.5 years to circle the Sun, so it typically spends a lot of time in each constellation it traverses. It crosses from Sagittarius to Capricornus in March 2020, ending a 28-month foray through the Archer's stars. But its longest stretch comes within the confines of Virgo the Maiden. The chart shows the percentage of time the ringed planet will reside in each constellation from March 2020 until it returns to the same position three orbits from now, in July 2108. – RICHARD TALCOTT



ASTRONOMY: RICK JOHNSON

FAST FACT

Saturn's orbit tilts 2.5° to the ecliptic, enough that it slices through two non-zodiacal constellations: Cetus and Orion.

3.7 million

The speed, in mph (6 million km/h), at which astronomers recently clocked a star fleeing our galaxy. Researchers believe the star's speed results from a close encounter with the Milky Way's supermassive black hole.

planets or, according to the new study's researchers, primordial black holes.

"Capture of a free-floating planet is a leading explanation for the origin of Planet Nine," wrote the authors in the study, "and we show that the probability of capturing a primordial black hole instead is comparable."

According to Konstantin Batygin of Caltech, who has been a primary proponent of the Planet Nine hypothesis but was not involved in the new study, it's definitely possible that a primordial black hole could replace Planet Nine in their model. But that doesn't mean it should. "The important thing to understand here is that all that the calculations can tell is the mass of Planet Nine, not its composition," Batygin tells *Astronomy*. "So, in principle, Planet Nine can be a planet, a potato, a black hole, a hamburger, et cetera, as long as its orbital parameters are right."

Though Batygin isn't convinced a primordial black hole roaming the outer solar system would be a more natural fit than Planet Nine, he admits he's hesitant to write off the new idea completely. Or, as he put it: "I always like to keep an open mind." – JAKE PARKS

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QUICK TAKES

NESTED BLACK HOLES

New research suggests the disks of supermassive black holes could have smaller black holes merging within them. If true, this could help explain the formation of the roughly 50-solar-mass black holes found by the Laser Interferometer Gravitational-wave Observatory.

BON VOYAGE

Voyager 2 passed into interstellar space in November 2018. Scientists have described the milestone in five recent papers, including one that found surprising signs of charged particles "leaking" from the heliosphere, the bubble of space carved out by the Sun's influence.

CASE-ING PLANETS

The European Space Agency's ARIEL mission, planned for launch in 2028, will closely study the atmospheres of about 1,000 exoplanets. Aboard the spacecraft, NASA's CASE instrument will help determine whether these alien skies are cloudy, hazy, or clear.

STARLINK GROWS

On November 11, SpaceX launched its second batch of 60 Starlink satellites into orbit; they are intended to further the company's goal of providing global internet coverage through a combined fleet of about 12,000 total satellites by the mid-2020s.

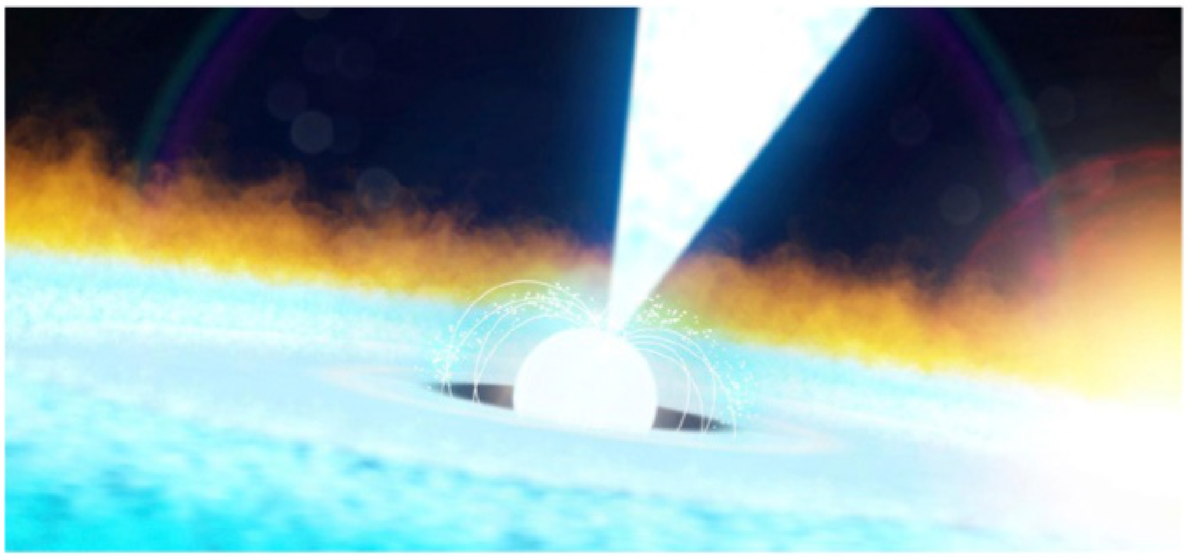
SMALLEST DWARF

New observations show asteroid Hygiea, the fourth-largest object in the main belt, is spherical. This could make it the solar system's smallest known dwarf planet.

NOT SO GOLDILOCKS

Rice University scientists modeled how stars' extended magnetic fields impact the habitability of close-in "Goldilocks" exoplanets, finding the fields could strip a planet's life-protecting atmosphere away in as little as 100 million years. – J.P.

NICER sees brightest X-ray burst yet



NASA'S GODDARD SPACE FLIGHT CENTER/CHRIS SMITH (USRA)

IN A FLASH. X-ray bursts from a neutron star, shown in this artist's concept, eject hydrogen and helium from the surface of the star. Additionally, X-rays from the explosion can bounce around the swirling accretion disk of gas around the neutron star (blue and orange), causing the object to flicker.

The Neutron star Interior Composition Explorer (NICER) sits outside the International Space Station, scanning the skies for blasts of X-rays from neutron stars — the dense remnants of massive stars — and black holes. On August 20, the instrument saw a sudden spike of X-rays that released as much energy in 20 seconds as the Sun puts out in about 10 days.

This burst was the brightest NICER had ever recorded. And it showed a combination of features that astronomers hadn't seen together in a single event. Astronomers studying the burst reported their findings October 23 in *The Astrophysical Journal Letters*.

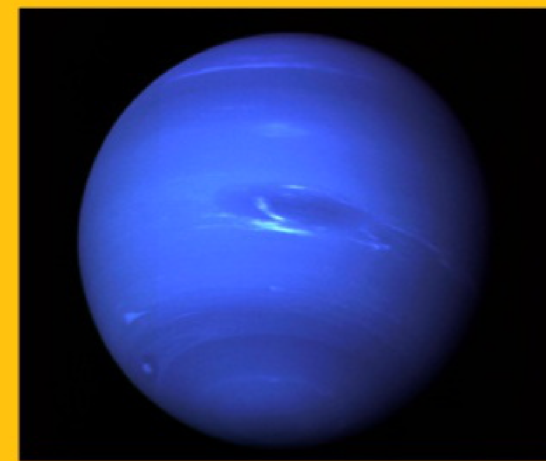
X-ray bursts often come from neutron stars in binary systems containing a neutron star and another object. This flash came from SAX J1808.4–3658, or J1808 for short, a neutron star partnered with a brown dwarf, which is an object too massive to be a planet but not massive enough to be a star.

As J1808 pulls hydrogen off its companion, the gas accumulates on the neutron star. As more gas falls on the star, the intense heat and pressure turns some of this hydrogen into helium. When enough hydrogen settles onto the surface, the added weight makes the helium suddenly fuse into carbon — and explode.

That's what caused the August burst. Astronomers saw evidence that the explosion blew material off of the neutron star in two layers. A layer of hydrogen was ejected first, followed by a layer of helium. The helium layer outraced the hydrogen; then the helium slowed, stopped, and settled back down onto the neutron star's surface. After that, J1808 grew brighter by about 20 percent before finally fading.

NICER has previously seen X-ray bursts corresponding to the ejection of a hydrogen or helium layer, but not both in a single burst like this, Peter Bult at NASA's Goddard Space Flight Center, one of the paper's authors, tells *Astronomy*. Additionally, astronomers cannot explain the brief brightening episode. Finally, NICER spotted X-ray "flickers" from X-rays reflecting off the swirling disk of hydrogen surrounding J1808, which is made of material pulled off the brown dwarf.

"I'm most excited by the fact that we see these various phenomena in the same burst," Bult says. Taken together, these observations could tell scientists much about the physics of X-ray bursts and neutron stars. — ERIKA K. CARLSON, A.K.



NASA/JPL-CALTECH

THE DANCE OF NEPTUNE'S MOONS

Neptune's moons Naiad and Thalassa are a matched pair. Each only about 60 miles (100 kilometers) wide, they orbit the ice giant every 7 and 7.5 hours, respectively. And yet, they don't collide, thanks to strange cosmic choreography called an orbital resonance.

Resonances are common in the solar system — for example, Pluto circles the Sun twice for every three orbits Neptune completes. Objects in an orbital resonance are more stable, which is why these patterns pop up so frequently.

But the resonance between Naiad and Thalassa is unique in the solar system so far. Naiad's orbit is tilted almost 5° relative to Thalassa's. For an observer on Thalassa, Naiad appears to weave up and down in a wavelike motion. The motion keeps Naiad about 2,200 miles (3,540 km) away from Thalassa every time it laps the slower-moving moon.

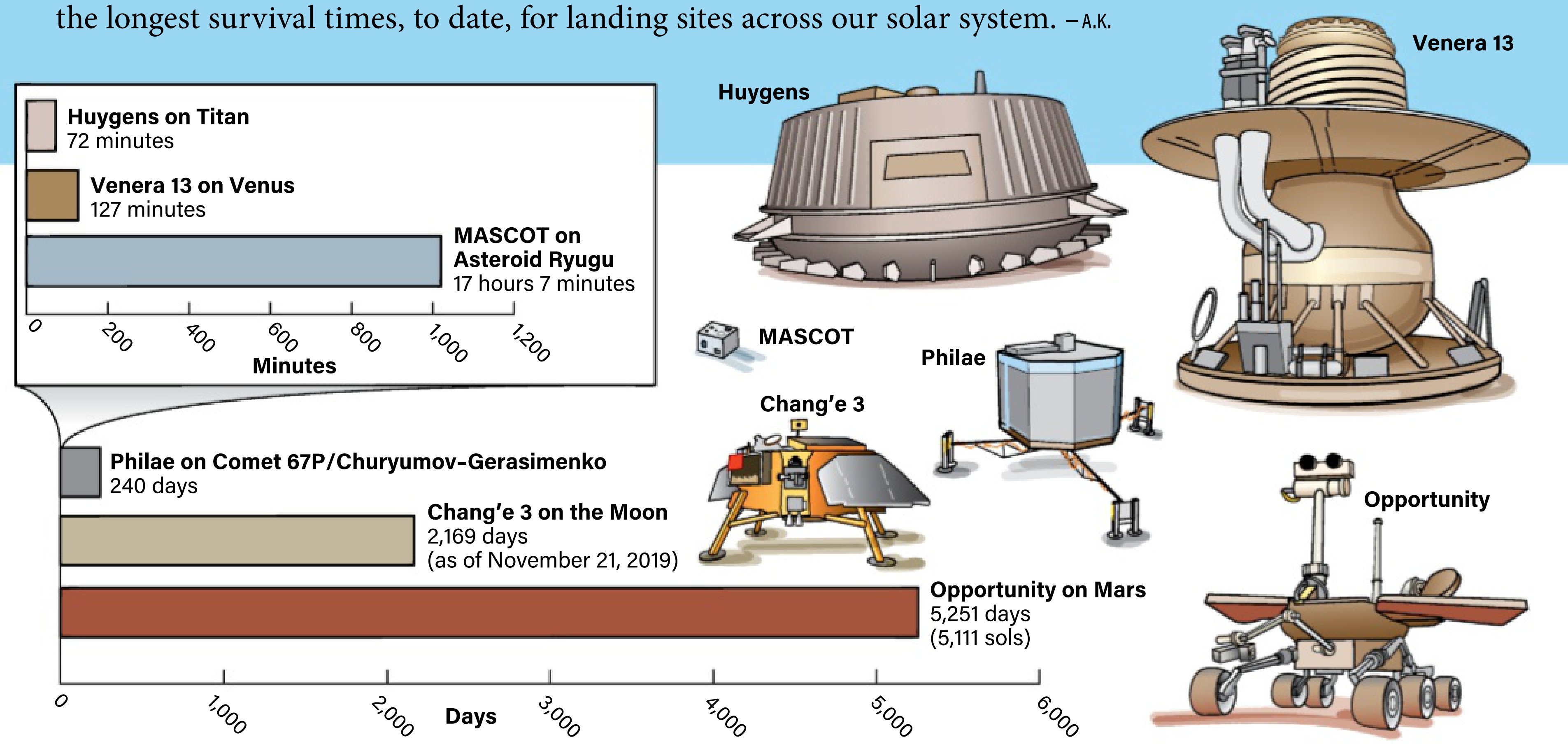
The newly discovered resonance was published March 1, 2019, in *Icarus*. According to co-author Marina Brozović of NASA's Jet Propulsion Laboratory, the current arrangement implies that an orbital resonance with some other moon must have bumped Naiad into this tilted orbit. After that, Naiad and Thalassa were able to begin their dance. – E.K.C., A.K.

SPACECRAFT SURVIVAL RATES

MEASURED DAYS. Humans have sent numerous probes to other worlds, allowing robots to set foot(pads) where we cannot. But some landing sites are harsher than others. Although many missions today, such as those sent to Mars or the Moon, are designed to last months or years, several landers that have touched down on other worlds survived only minutes or hours before going dark. Here's a list of the longest survival times, to date, for landing sites across our solar system. – A.K.

FAST FACT

Apollo 17 was the longest crewed landing on another world. The astronauts spent a total of about 75 hours on the Moon's surface, from landing to liftoff.



ASTRONOMY: ROEN KELLY

5,000

The number of fiber-optic cables in the Dark Energy Spectroscopic Instrument at Kitt Peak National Observatory. Each cable can image an entire galaxy to determine its position and motion in space.

Exploring ancient life in Australia

In preparation for the upcoming launches of NASA's Mars 2020 rover and the European Space Agency's ExoMars rover, a team of scientists recently traveled to the Pilbara region of Australia to study ancient examples of life. Specifically, the researchers analyzed stromatolites, which are the oldest confirmed fossilized life-forms on Earth. These ancient microbes resembled pond scum and were fossilized after becoming trapped in sea sediment billions of years ago. By examining the microbes' remains, the researchers say they'll be better prepared to recognize any stromatolite-like fossils that the Mars rovers might uncover. – J.P.

NASA/JPL-CALTECH

WHERE THERE'S WATER. The suspected global ocean of liquid water beneath the surface of Jupiter's moon Europa is one place humans plan to search for life. This artist's concept shows a massive plume of water erupting from the moon's surface. NASA/ESA/K. RETHERFORD/SwRI

Water vapor detected in Europa's atmosphere

» Jupiter's moon Europa has an icy shell that astronomers have long thought conceals a liquid water ocean beneath. Now, scientists have finally made the first direct measurement of water vapor trapped in Europa's atmosphere, which serves as the most compelling evidence yet that water plumes are indeed erupting from the icy moon's surface.

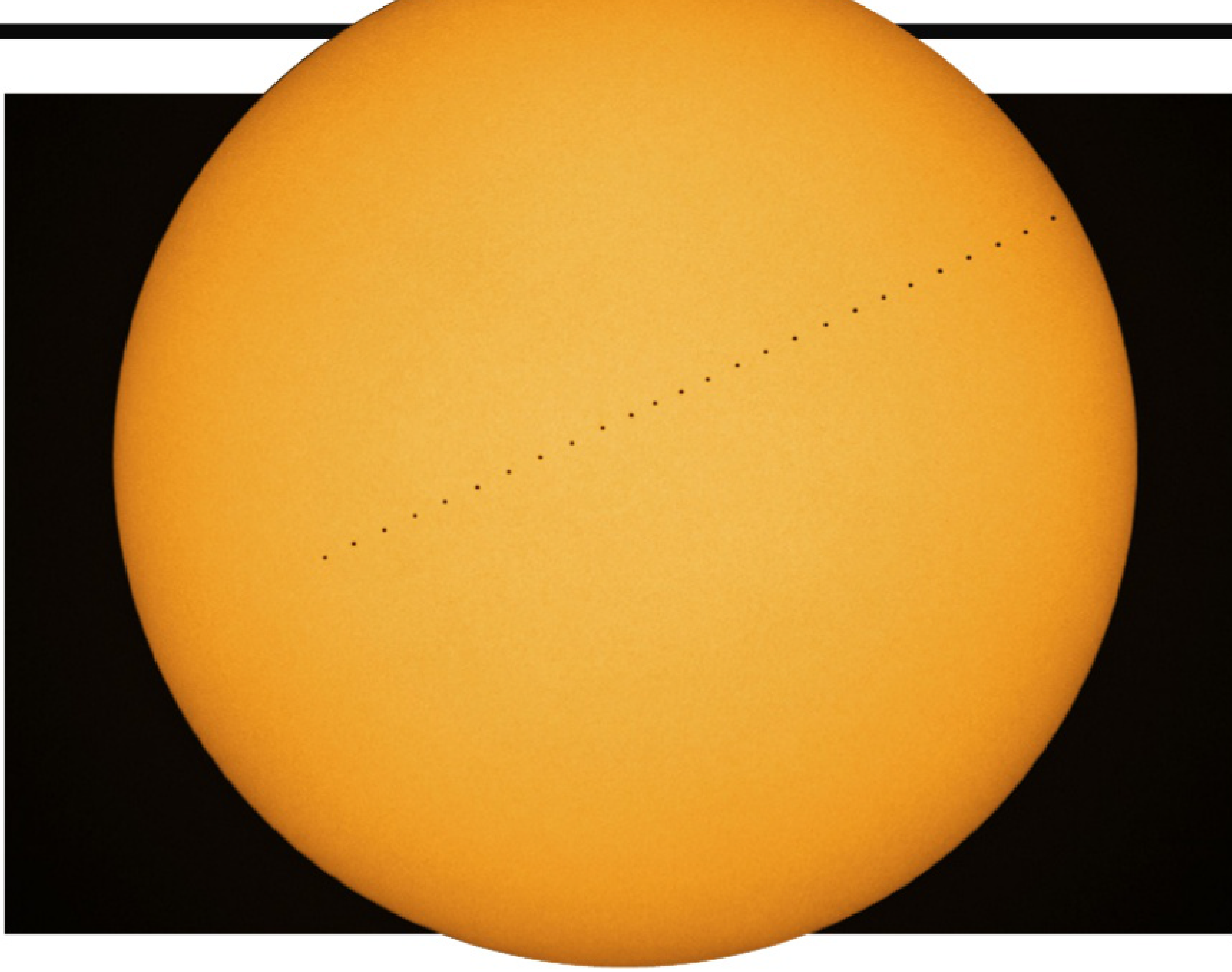
The new measurements also imply that, outside of plume events, Europa's atmosphere likely has less water vapor overall than previously thought. The findings were published November 18 in *Nature Astronomy*.

Scientists have known since the 1960s that Europa is likely home to water ice and a liquid water ocean beneath its surface. They even predicted that radiation from Jupiter would bombard the moon's icy surface, thereby releasing water vapor into its atmosphere. Previous observations have spotted plumes erupting into the moon's atmosphere; however, researchers have been unable to confirm whether they contain water vapor. In the new study, researchers used Keck Observatory to observe the moon on 17 different dates from February 2016 to May 2017, searching for specific infrared wavelengths of light emitted by water vapor. On one night, April 26, 2016, they saw it when their instruments measured a surprisingly large amount or water vapor — roughly 2,000 metric tons.

Although the researchers failed to find signs of water vapor on the other 16 nights, that doesn't mean it wasn't hiding there all along. In fact, the team believes some water vapor exists in Europa's atmosphere all the time due to Jupiter's radiation. So, the only reason they didn't consistently spot it, they said, is that the water vapor is probably usually just too scarce for instruments to detect.

Overall, the latest measurements imply that the typical amount of water vapor in Europa's atmosphere at any given time is probably less than previously thought. This means that the standout measurement in April 2016 likely came from a one-time event, like a plume of water erupting from the moon's surface. Fortunately, upcoming space missions like Europa Clipper and the JUpiter ICy moons Explorer, or JUICE, will take a much closer look at Jupiter's smallest Galilean moon.

"I'm really looking forward to follow-up studies of Europa and other ocean worlds," Lucas Paganini, a NASA planetary scientist and one of the recent paper's authors, tells *Astronomy*. "It has been difficult to detect water in liquid form. These detections of water in vapor form, I think, [are] the closest thing we have in the search for liquid water environments." — E.K.C., J.P.



CHRIS COOK

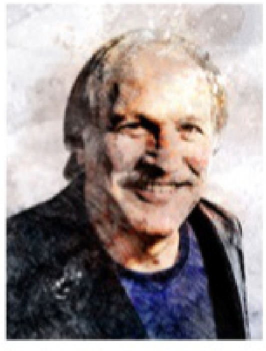
Mercury transits the Sun

On November 11, 2019, the planet Mercury made its last transit across the face of the Sun until 2032. This photographer captured a 1⁄400-second exposure of Mercury's transit every 10 minutes from 8:45 A.M. EST to 12:55 P.M. EST using a Canon EOS 6D camera, an Astro-Physics 130mm EDT refracting telescope, and a Baader AstroSolar filter. — J.P.

Subitize the sky

How many stars can you count — without counting?

How many Pleiades can you subitize? This well-known pattern of stars lets you instantly determine how many stars appear to your peering eyes without actually counting them up, one by one. SERGIY VAKULENKO (FLICKR)



BY BOB BERMAN
Join me and Pulse of the Planet's *Jim Metzner in my podcast, Astounding Universe, at* **www.astoundinguniverse.com**

If you enjoy new vocabulary words, you'll probably get pleasure from the word *subitize*. It's the ability to immediately perceive how many objects you're looking at without counting them. Some elementary school and kindergarten educators now utilize the concept, which was first advocated for in the early 20th century.

Adults generally have no trouble subitizing up to four objects, and some can do a bit better. Try it yourself with vitamin tablets or grapes. If you place three pills on a table, you won't have to mentally count out 1-2-3. Instead, a quick glance instantly tells you three pills are present.

Adults generally have no trouble subitizing up to four objects, and some can do a bit better.

Try it with four. Then five, which is a bit harder, and which studies show will delay your "count" by a quarter of a second. Some people can subitize higher numbers, but accuracy normally declines after four.

Patterns can help us cheat when we're subitizing. Most famously, the pips on a set of dice are sufficiently familiar that the majority of us can glance at a die and immediately distinguish between the face that depicts four and the face that displays six.

You might already see how this could take us to astronomical observing. Most of us probably already subitize when we're setting up for an astro-session. We may routinely use the same favorite three eyepieces, for example, and once we're out in the field, a simple glance assures us they're all present. At a public night with a local astronomy club, a mere glance tells us if four telescopes are pointing at the clouds. But the real usefulness arrives when we subitize celestial objects.

We immediately perceive if Jupiter is accompanied by three Galilean satellites, as opposed to all four. And since one of them — Ganymede — is distinctly brighter than the others, while only one — Callisto — wanders more than 10 Jupiter widths from the planet (and is also the dimmest), we can even "subitize" their identifications, meaning we grasp it all instantly. OK, you've got to recognize a third moon to identify all four. The easiest instant-glance method: Of the remaining two, both of which are never far from Jupiter, Europa is a discernible 0.3 magnitude dimmer than Io.

Voilà. Instant subitization of the Galilean satellites and an almost-as-fast identification of each one. Announce the info to your companions, seem like a genius, throw your scope back into your SUV, and drive away. All pointlessly accomplished in 14 seconds.

Under dark skies, the Pleiades beg for your subitizing skills. Average eyes can see six stars under most suburban conditions. If you already know that six falls within your subitization skill set, you're in business. Especially since here, the pattern provides extra assurance. Experienced observers know the Pleiades' outline in their sleep: It resembles a little dipper. Like pips on a die, this makes their total number easy to discern and also lets you instantly spot any additional members that excellent skies or a recent optometrist visit may turn up.

Where I live, eight stars are always visible to the naked eye, and spying 11 is not uncommon. The easiest "extra" Pleiad (when using the singular, you're supposed to say "PLEE-ad") is the star Pleione ("PLEE-oh-nee") on the upper left, just above Atlas, the leftmost bright member. In the always-enjoyable one-upmanship part of an astro-meet, you could be the first to claim subitization of the Seven Sisters.

Probably we all subitize the Hyades too, whose five main stars and easy V shape make it a snap. So, let's at least stretch it to six by including Lambda (λ) Tauri, the star the entire V points to like an arrow. And, bingo, you can't deny the Hyades are subitizable.

Bet you've never read that last sentence anywhere else. If you have, let us know and we'll send you a pair of giant fuzzy dice.

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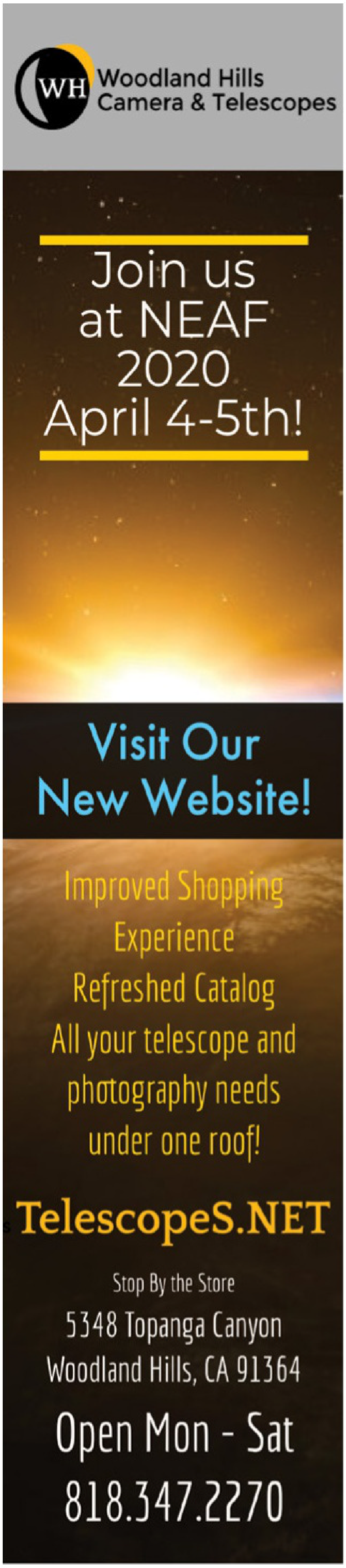

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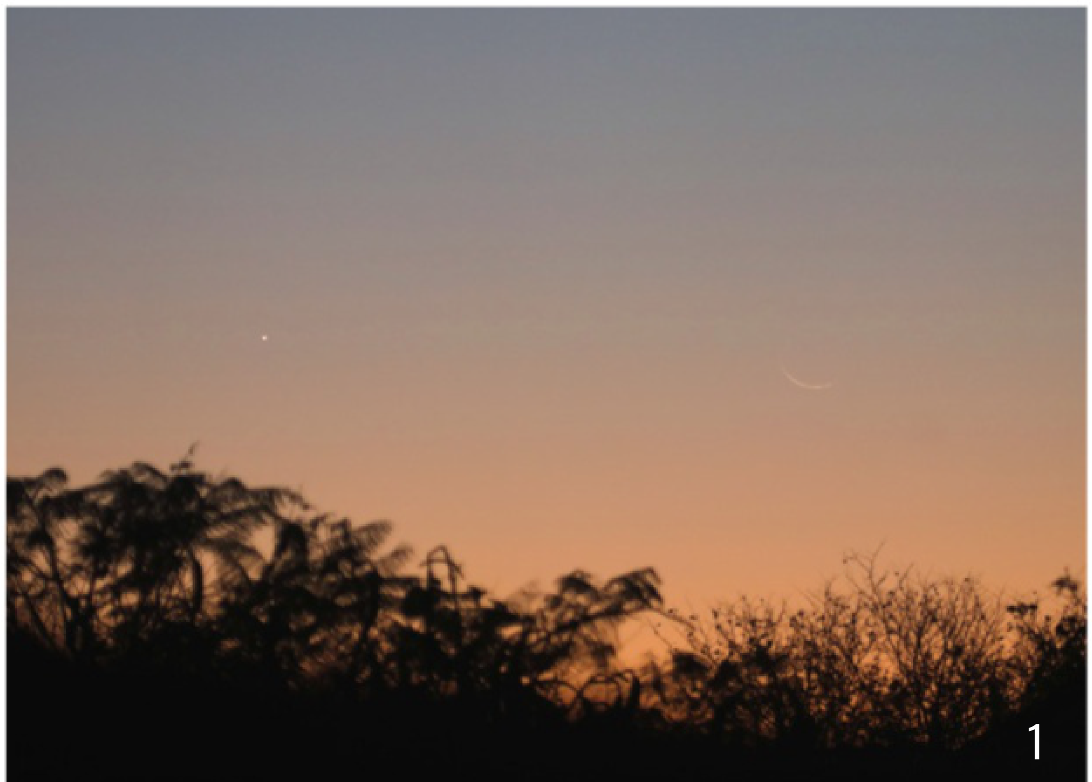
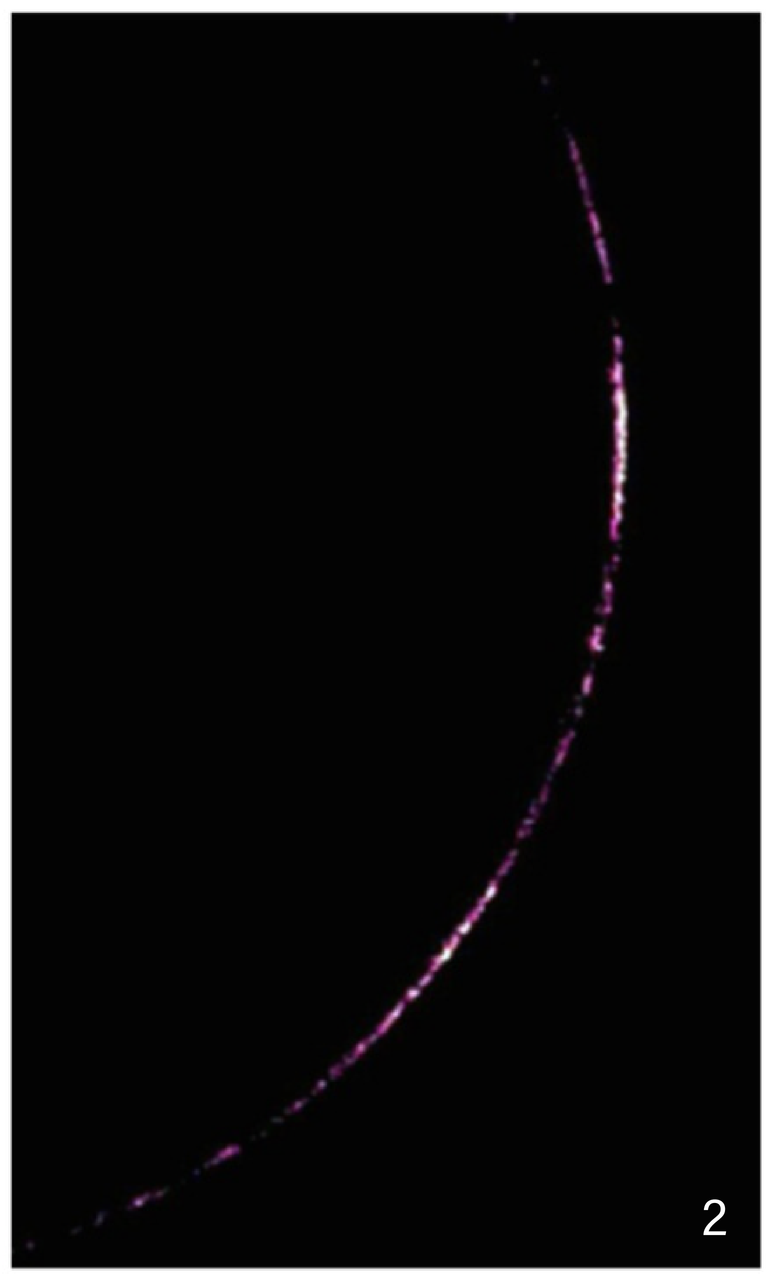
The lunar blackdrop effect

Take a closer look at the thin crescent Moon.



1. A 21-hour-young Moon (with Cheshire-cat grin) and Venus share the low western sky as seen from Maun, Botswana, on September 29, 2019.

IMAGES BY STEPHEN JAMES O'MEARA, UNLESS NOTED



In visual astronomy, it's easy to miss the forest for the trees. Sometimes, we become so focused on what we want to see that we can easily miss out on what else there is to see — even if it isn't real.

The thin lunar crescent is a perfect example. How many times have I looked at the old Moon in the new Moon's arms and missed (or ignored) an amazing, well-known phenomenon usually associated with transits of Venus? How appropriate that the young Moon wears a mischievous Cheshire-cat grin early in each of its lunations.

Saber's beads

First, the lunar blackdrop is different from what's become informally known as Saber's beads, a phenomenon occurring when the Moon is less than one day from its New phase. Then, it shows staggered brightness peaks along the crescent, reminiscent of mini-Bailey's beads.

Since Illinois amateur astronomer Stephen Saber first described "his" beads in 2006, others have linked his description to all manner of phenomena. The oldest are Galileo's 1609 telescopic observations: The celebrated astronomer noted in *The Sidereal Messenger* that at "the ends of the upper and lower cusps also certain bright points, quite away from the rest of the bright part, began to rise out of the shadow." Modern telescopic

BY STEPHEN JAMES O'MEARA
Stephen is a globe-trotting observer who is always looking for the next great celestial event.

2. Stephen Saber's image of a young Moon shows a thin crescent displaying dark areas between lunar brightness peaks, giving one the impression of Bailey's beads as seen during a total solar eclipse. STEPHEN SABER

3. As Galileo first spied through his telescope in 1609, the cusp of the Moon's limb can appear segmented with bright spots appearing through the darkness. This image shows that phenomenon beyond the southern cusp on an approximately two-day-old Moon.

4. Blackdrop effects (both thick and thin) appear on a 21-hour-young Moon that stood only 4° above the western horizon. These black "pajama stripes" waxed and waned with the steadiness of Earth's atmosphere, becoming more prominent under less-than-perfect conditions.

views show a broken arc (or necklace) of illuminated peaks all along the lunar limb that Saber also imaged when the Moon was extremely thin.

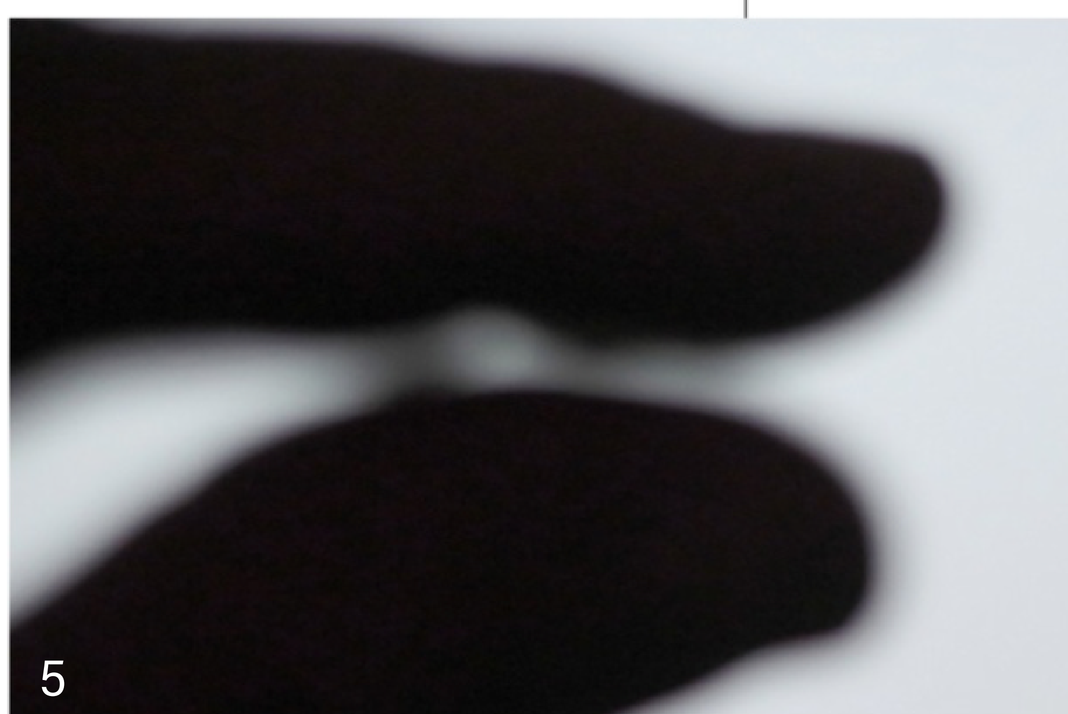
The Moon in striped pajamas

The lunar blackdrop effect is different. When the Moon is less than one day from New, an observer can see multiple blackdrop effects along the slender lunar crescent under imperfect seeing conditions. I first realized this on the night of September 29, 2019, when the 21-hour-young lunar crescent appeared only 4° above the western horizon.

When the Moon is less than one day from New, an observer can see multiple blackdrop effects.

Unlike Saber's beads, these dark lunar "pajama stripes" were illusions caused primarily by diffraction — the bending and interfering of light waves — which was intensified by the blurring effects of Earth's atmosphere. Undoubtedly, the Moon's complex interplay of light and shadow along the thin crescent enhanced the phenomenon.

The Moon was only about one day from perigee (its closest point to Earth during any orbit), which helped make the phenomenon readily apparent to the unaided eyes. However, the truth came forth through 8x42 binoculars, which showed the blackdrop effect coming and going depending on the seeing, especially as the Moon sank ever closer to the horizon.



5. The blackdrop effect due to diffraction appears at different locations in the irregular spacing between two fingers that are not touching. The lower finger represents the dark sky, the top finger represents the dark lunar terminator, and the space between the fingers represents the thin lunar crescent. (The fingers are intentionally placed out of focus to represent the blurring effects due to poor atmospheric seeing.)

When crisp, the Moon was an unbroken smile; under heat turbulence rising from the surrounding desert sands, the Moon fractured into a toothy Cheshire-cat smile, with the dark gaps waxing and waning in the unstable air.

Have you also seen this effect? If so, send your impressions to sjomeara31@gmail.com.

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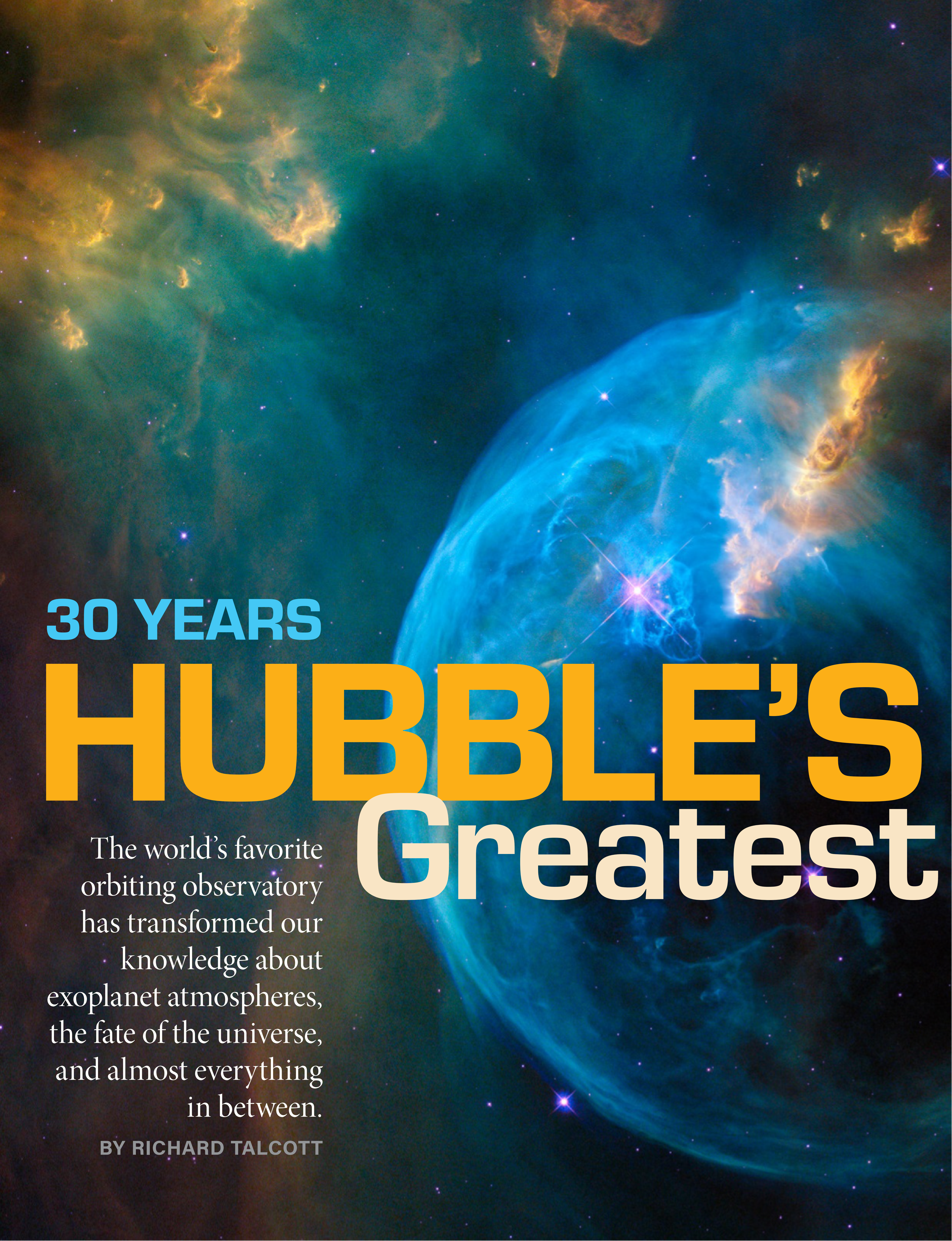


30 YEARS

HUBBLE'S Greatest

The world's favorite orbiting observatory has transformed our knowledge about exoplanet atmospheres, the fate of the universe, and almost everything in between.

BY RICHARD TALCOTT

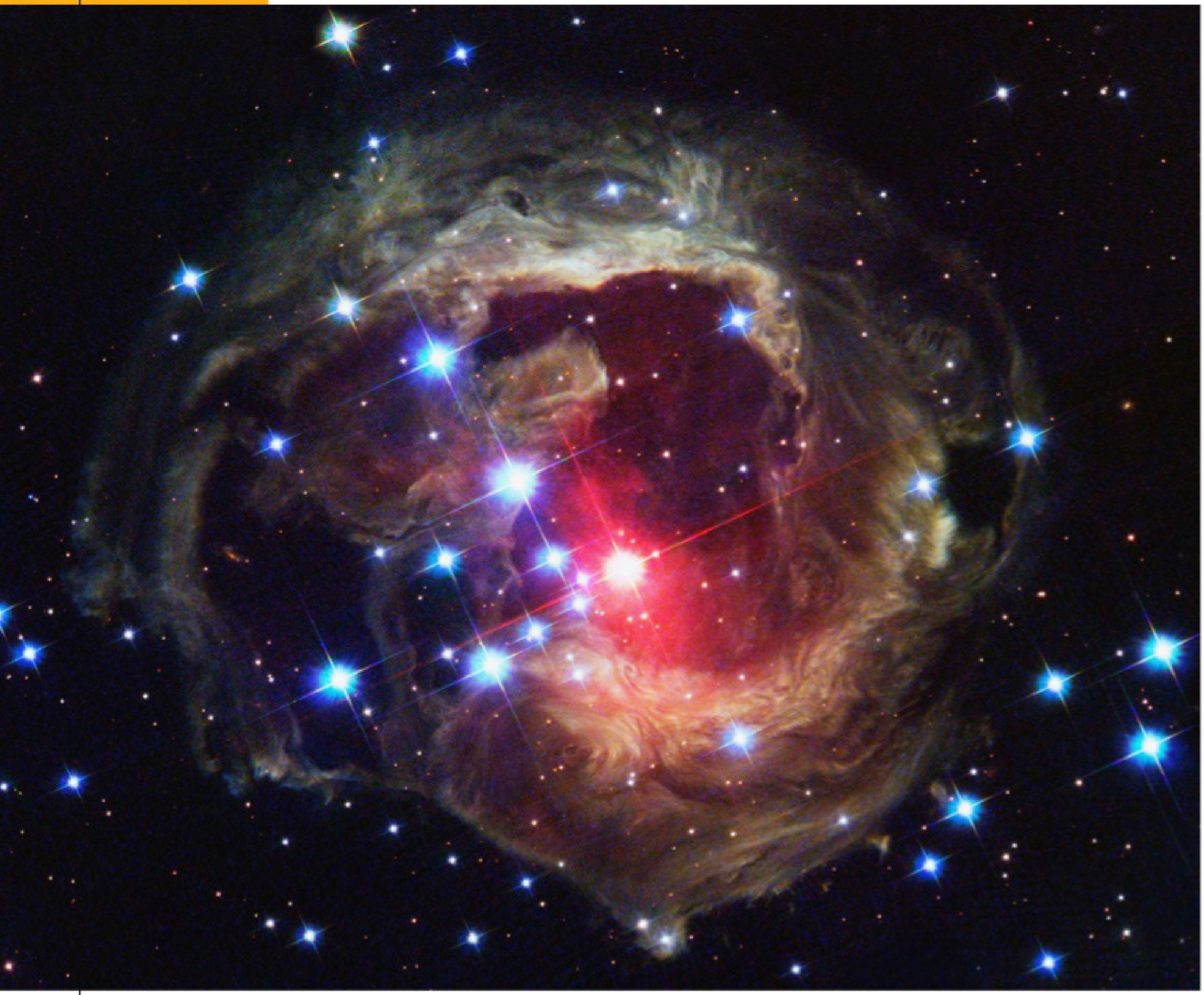
Hits

IT'S HARD TO BELIEVE that nearly half the people alive today have never known a world without the Hubble Space Telescope. The space shuttle *Discovery* blasted off with its precious cargo from Kennedy Space Center on April 24, 1990, and the next day, the shuttle's five-person crew deployed the school-bus-sized observatory in low Earth orbit. In the 30 years since, Hubble has helped redefine our universe, tackling problems that had plagued astronomers for decades, as well as discovering new mysteries no one imagined.

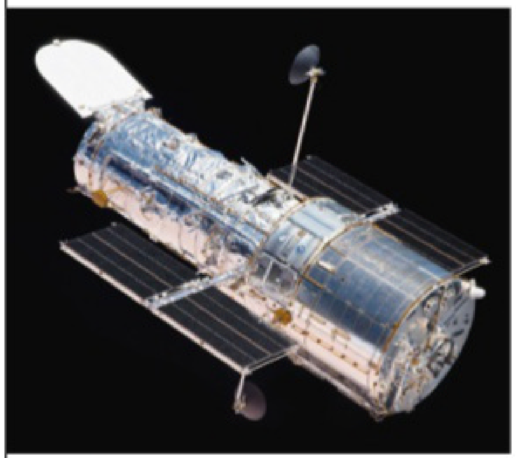
Of course, Hubble's history has not been without glitches. The most critical appeared within weeks of its deployment. Early images revealed that the telescope's 2.4-meter mirror was flawed — its edges were too flat by 2 micrometers, or roughly 1⁄50 the width of a human hair — and could not focus light sharply. For a telescope whose whole raison d'être was to deliver crystal-clear views of the cosmos from above the distorting effects of Earth's atmosphere,

The space shuttle *Discovery* lifts off from Cape Canaveral, Florida, on April 24, 1990. One day later, shuttle astronauts would deploy the Hubble Space Telescope on its 30-year-and-counting mission. NASA

Stellar winds from a massive star (the image's brightest star) carved the intricate contours of the Bubble Nebula (NGC 7635). The bubble has a bluish tinge, thanks to short-wavelength radiation emanating from ionized oxygen atoms. NASA/ESA/THE HUBBLE HERITAGE TEAM (STScI/AURA)



In January 2002, the star at the center of this image flared to became one of our galaxy's most luminous suns. This view from October 2004 captures surrounding shells of dust lit up by the eruption. NASA/ESA/THE HUBBLE HERITAGE TEAM (STScI/AURA)



The Hubble Space Telescope floats free in low Earth orbit after astronauts completed the fifth and final servicing mission in May 2009. With its new complement of instruments, it was ready for the 21st century's second decade. NASA

Hubble serves as a planetary weather satellite, keeping tabs on the atmospheres of our neighbors. In June 2019, it snapped this image of Jupiter showing the Great Red Spot significantly smaller than it was 30 years before. NASA/ESA/A. SIMON (GSFC)/M.H. WONG (UC, BERKELEY)

the imperfection was more than disheartening.

Fortunately, NASA designed Hubble to be serviced regularly. On December 3, 1993, a team of seven astronauts rocketed into orbit aboard the space shuttle *Endeavour*. Their most important task: Install two new instruments that would serve as "eyeglasses" and transform fuzzy images into crystal clarity.

Four subsequent servicing missions — the final one in May 2009 — have completely revamped the observatory and made it into a 21st-century science machine. It has captured more than 1 million images of the cosmos, exploring objects as near as the Moon and as distant as some of the first galaxies to form in the early universe. And it has studied myriad examples of almost every type of target that lies between.

Planetary weather satellite

When people think of Hubble, most picture stunning images of Milky Way nebulae and colorful galaxies. But scientists often set their sights closer to home. No spacecraft has visited Uranus or Neptune since the 1980s, leaving Hubble and large ground-based telescopes to take up the slack. The space telescope has shown Uranus, which appeared as a bland, bluish ball when Voyager 2 flew past in 1986, to be an active world boasting bright clouds of methane. And in Neptune's atmosphere, Hubble has tracked massive storms, some as big as Earth, propelled by winds that average 900 mph (1,450 km/h).

Hubble also has tracked storms on Jupiter and Saturn, augmenting observations made by orbiting spacecraft. And it was the space telescope that first detected evidence that water vapor may be

erupting from Jupiter's moon Europa. The plumes likely represent material from an underground ocean venting through the moon's icy crust.

Hubble played a key role in the success of NASA's New Horizons' mission to Pluto. Between 2005 and 2012, the orbiting observatory discovered four new targets for New Horizons: the small moons Hydra, Nix, Kerberos, and Styx. But, more importantly, observations made over several years mapped light and dark regions on the dwarf planet's surface. The brightest of these areas so intrigued New Horizons scientists that they targeted the flyby so it would be front and center at closest approach in July 2015. That's how we learned so much about the heart-shaped, nitrogen-ice glacier now known as Tombaugh Regio. Hubble also discovered the Kuiper Belt object 2014 MU_{69}, since named Arrokoth, that New Horizons flew past January 1, 2019.

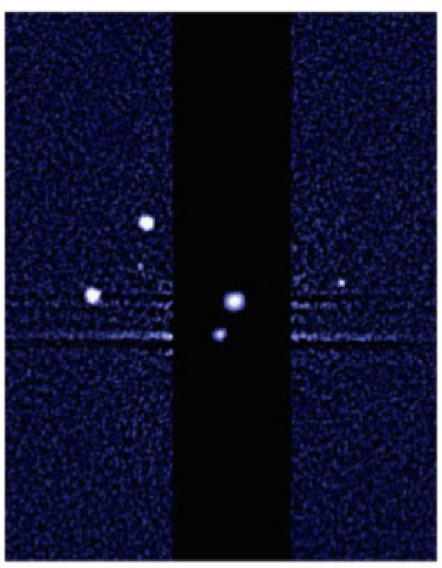
Milky Way treasures

Beyond the solar system, Hubble opened a new window into star birth and star death. Raised above Earth's obscuring atmosphere, the space telescope collects not only visible light but also ultraviolet and infrared radiation (light with wavelengths slightly shorter and longer, respectively, than what we can see). The extra information lets scientists probe deeper into the thick clouds of gas and dust that harbor young stars.

This dark pillar of cold gas and dust in the Eagle Nebula (M16) towers some 9.5 light-years high, roughly twice the distance between the Sun and the next nearest star. The pillar shrouds recently formed stars that have yet to break out from their natal cocoons. NASA/ESA/THE HUBBLE HERITAGE TEAM (STScI/AURA)

One of the Milky Way's premier star factories is the Carina Nebula (NGC 3372), which came to life about 3 million years ago when stars first ignited in a cloud of molecular hydrogen. In this view, jets of gas erupt from infant stars emerging from their birthplaces. NASA/ESA/M. LIVIO AND THE HUBBLE 20TH ANNIVERSARY TEAM (STScI)

Hubble has made several discoveries in our solar system, including four of Pluto's five moons. Pluto and previously discovered Charon lie in the less-exposed vertical bar, while Hydra, Nix, Kerberos, and Styx appear as fuzzy blobs to either side. NASA/ESA/M. SHOWALTER (SETI INSTITUTE)



Astronomers nicknamed this planetary the Butterfly Nebula (NGC 6302) because it looks like the beautiful insect through earthbound telescopes. Such objects are the death shrouds of stars like the Sun, which will reach this stage in 5 billion years or so. NASA/THE HUBBLE SM4 ERO TEAM

Now astronomers can observe fledgling stars in gaseous nebulae as they emerge from their birth cocoons. They can watch the hottest of these stellar youths excavate cavities in their surroundings and erode dust-filled pillars where new stars are trying to form. In the nearby Orion Nebula, Hubble revealed protoplanetary disks surrounding dozens of baby stars. These dusty disks appear to be the raw material nature uses to create planets.

When Hubble launched, scientists counted only nine planets in the universe. (This was before Pluto's demotion to dwarf planet status in 2006.) Since the early 1990s, astronomers have discovered more than 4,000 planets orbiting other stars. Although the space telescope contributed only a handful to this total, its spectrographs have analyzed the atmospheres of several exoplanets. Perhaps most intriguingly, Hubble has detected significant amounts of water vapor on a few of these worlds.

The lives of stars play out over millions, billions, and

sometimes trillions of years, and the space telescope has given astronomers front-row seats to study nearly every stage of stellar evolution. A star like the Sun will eventually puff off its outer layers, creating a glowing death shroud known as a planetary nebula. Hubble has explored dozens of these beautiful structures and found them to be far more complex than previously suspected. Instead of exhaling one dying breath, many Sun-like stars experience multiple death throes. Intricate shapes develop as newly ejected gas interacts with material from older eruptions.

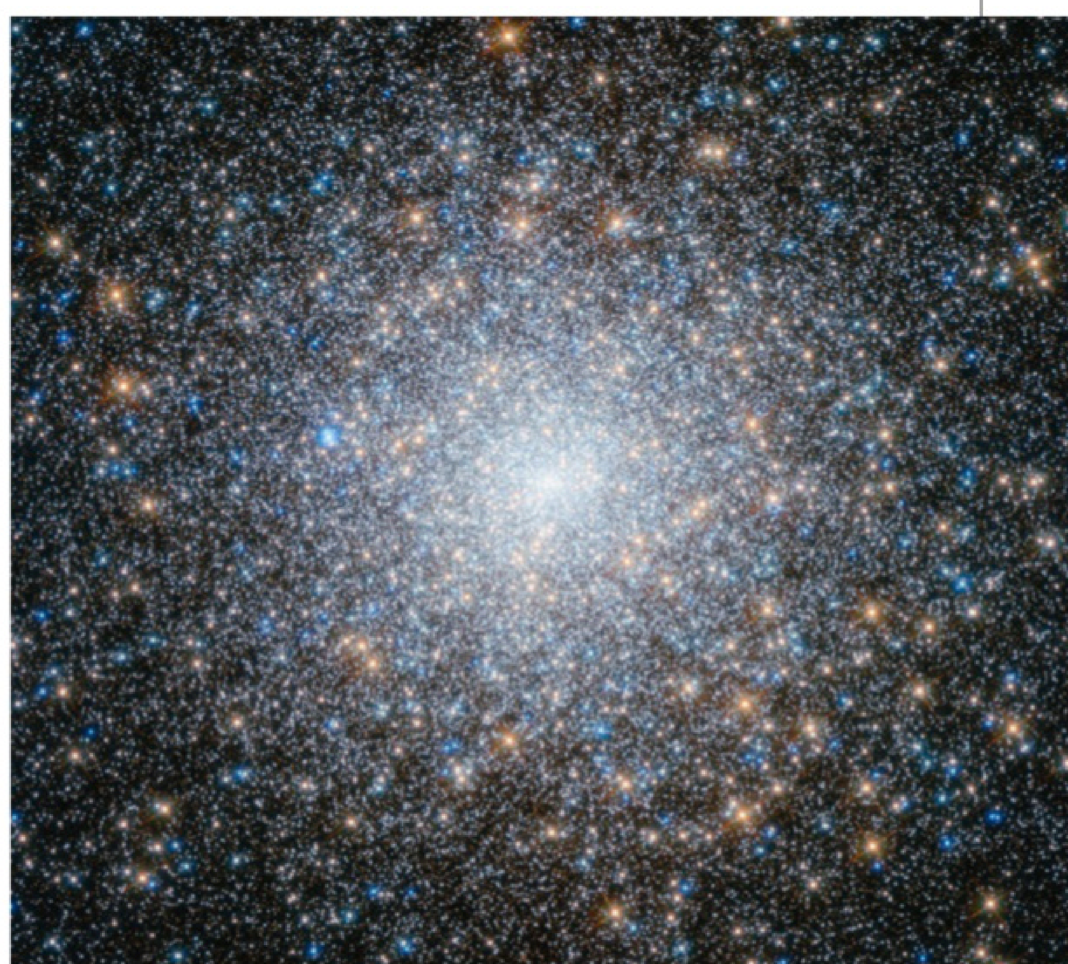
Massive explosions

Not all stars are destined to die in relative peace. Stars that begin life with more than 8 or so solar masses exit this universe in violent supernova explosions. These titanic blasts seed the cosmos with heavy elements while leaving behind a highly compressed stellar core — either a neutron star or black hole. Hubble has studied the remnants of these explosions, tracing the elements ejected in the blasts and watching as their gaseous tendrils evolve slowly with time.

Perhaps most importantly, the space telescope has tracked the remnant developing around the site of Supernova 1987A, a supergiant star that exploded in the Large Magellanic Cloud (LMC) — the Milky Way's largest satellite galaxy — in February 1987. Over the past 30 years, Hubble has witnessed the supernova's blast wave lighting up gas ejected by its progenitor star some 20,000 years earlier, and watched as the budding supernova remnant has taken shape.

The telescope's sharp eye has roamed all over the LMC. Its investigation of the Tarantula Nebula — the largest known star-forming region in the universe — resolved one longstanding mystery about the cluster in the Tarantula's heart. The cluster's core, dubbed R136a, appeared to be a single star weighing 1,000 solar masses or more, far bigger than astrophysicists deem possible. But Hubble resolved the cluster's dense core into several smaller stars. Although many tip the scale at more than 100 solar masses, making them among the heftiest stars known, they no longer violate physical law. Hubble's LMC observations show the telescope can see objects in nearby galaxies in the same

Globular star cluster M15 in Pegasus stands out as one of the densest globulars in the Milky Way Galaxy. Most of its mass resides in the core, where astronomers suspect an intermediate-mass black hole lurks. NASA/ESA



Spiral galaxy M106 in Canes Venatici helped nail down the Hubble constant. A water maser orbiting its central supermassive black hole yielded the spiral's distance, which Hubble scientists then used to help calibrate the Cepheid variable stars in the galaxy. NASA/ESA/THE HUBBLE HERITAGE TEAM (STScI/AURA)/R. GENDLER (FOR THE HUBBLE HERITAGE TEAM)

Like the Milky Way, NGC 1300 in Eridanus is a barred spiral galaxy that spans a bit more than 100,000 light-years. In such galaxies, spiral arms wind out from the ends of a star-filled bar. NASA/ESA/THE HUBBLE HERITAGE TEAM (STScI/AURA)

detail once possible only in the Milky Way.

Black holes (almost) everywhere

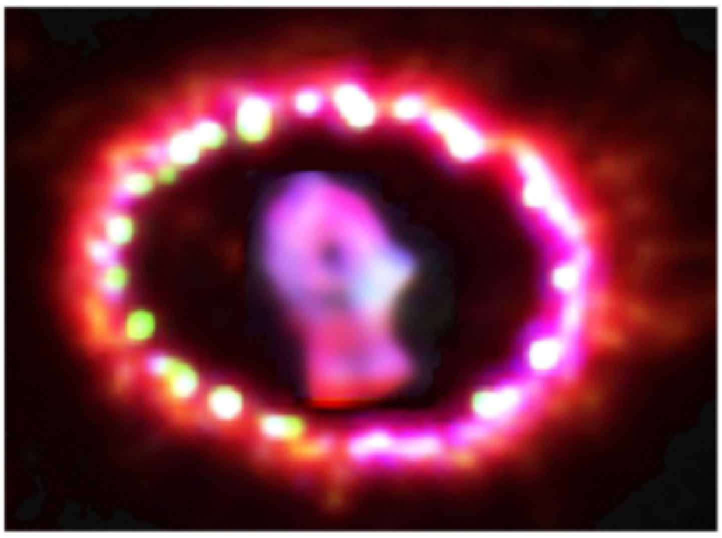
As Hubble cast its eye deeper into the universe, it made one discovery after another. Perhaps none stirred the public's imagination more than confirmation that black holes exist, and that they play vital roles in the evolution of galaxies. This signature achievement came in the 1990s, when Hubble examined the cores of M84 and M87, two of the largest galaxies in the nearby Virgo Cluster. This collection of thousands of galaxies lies some 50 million light-years from Earth. Using spectrographs to examine the rapid gas motions in the cores of these galaxies, the telescope revealed a supermassive black hole lurking at the center of each. Although earlier observations had hinted that black holes might exist in some galaxies, Hubble provided ironclad proof.

But even more importantly, Hubble found supermassive black holes to be common. Essentially every galaxy that possesses a dense, spherical bulge of stars surrounding its center hosts one of these beasts. These black holes range in size from perhaps 100,000 solar masses in dwarf galaxies to several billion solar masses in the biggest island universes. Hubble also showed that a black hole and its host galaxy are intimately linked: The masses of the stellar bulge and black hole grow in tandem.

Of course, Hubble doesn't restrict its gaze to the hearts of galaxies. It routinely explores individual stars known as Cepheid variables in nearby galaxies to pin down the expansion rate of the universe. Known as the Hubble constant after American astronomer Edwin Hubble, who discovered this expansion and for whom the space telescope is named, the rate plays a fundamental role in cosmology.

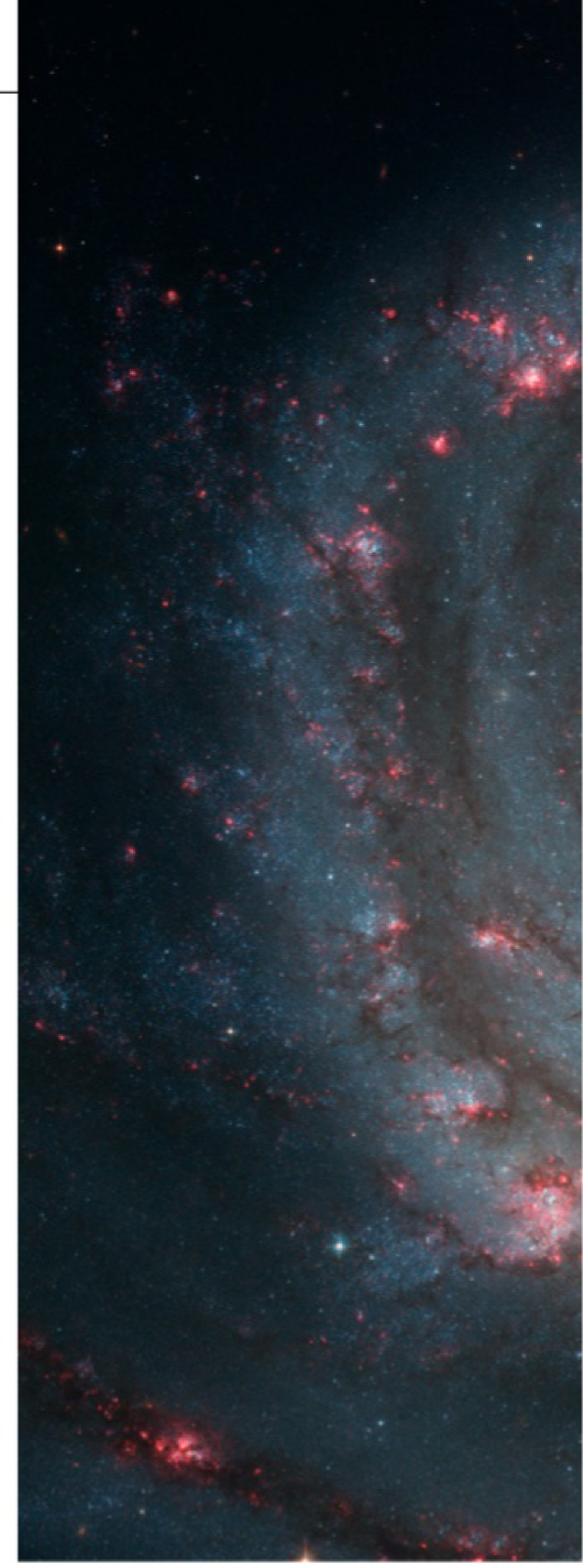
Cepheids serve as a critical rung on the cosmic distance ladder because the period of their pulsations tracks with their intrinsic luminosity. Observe how bright one appears in the sky and you can calculate how far away it is. Then measure how fast its host galaxy recedes from Earth and you

get the expansion rate. Thirty years of Hubble observations have pinpointed the expansion rate at 73 kilometers per second per megaparsec (one megaparsec equals 3.26 million light-years). Oddly enough, measurements from the European Space Agency's Planck satellite give a value of 67, and scientists have yet to



Hubble has studied the aftermath of Supernova 1987A throughout its 30 years in orbit. In this view, released in 2011, the progenitor star's tattered remains appear as an irregular blob at center, while the bright ring surrounding it consists of material the star released 20,000 years earlier that the supernova's shock wave is lighting up. NASA/ESA/PETE CHALLIS (HARVARD-SMITHSONIAN CENTER FOR ASTROPHYSICS)

The Crab Nebula (M1) represents the glowing tendrils of a massive star that earthbound observers saw explode nearly 1,000 years ago, in the year 1054. Astronomers have been able to deduce the nebula's expansion rate thanks in part to Hubble observations. NASA/ESA/ALLISON LOLL AND JEFF HESTER (ARIZONA STATE UNIVERSITY)

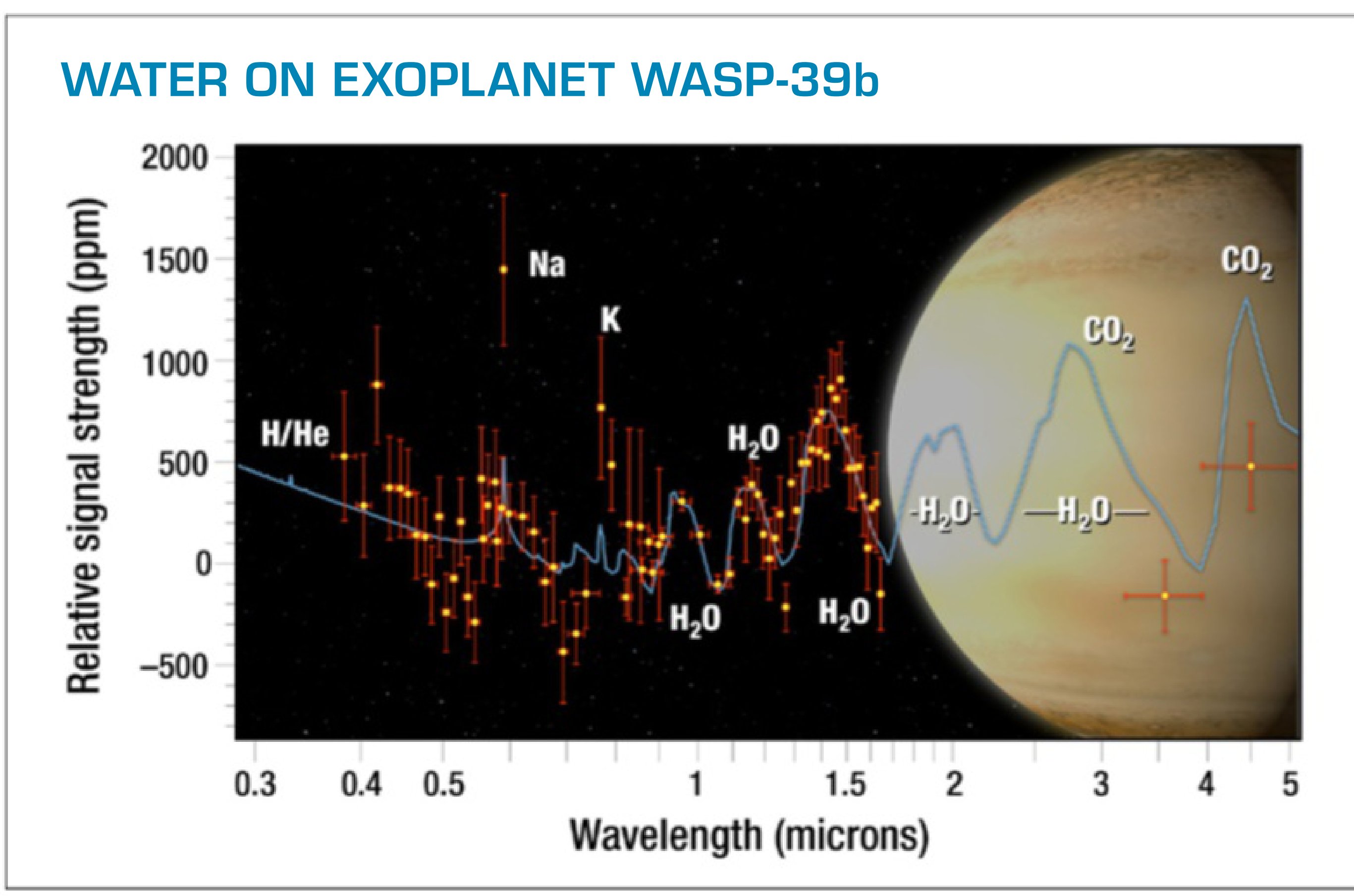


Galaxies like the beautiful Whirlpool (M51) played a key role in many of Hubble's cosmological discoveries. Such island universes are held together by dark matter, harbor supermassive black holes at their centers, help define the expansion rate of the cosmos, and fly away from one another at increasing rates thanks to dark energy. NASA/ESA/S. BECKWITH (STScI)/THE HUBBLE HERITAGE TEAM (STScI/AURA)

figure out how to bridge the gap. (See "Tension at the heart of cosmology" in the June 2019 issue.)

When the space telescope looks at galaxies in full, it usually finds a neighbor or two. In fact, Hubble has shown that collisions between galaxies are more the rule than the exception. Some of these collisions are in their early stages. For example, the Whirlpool Galaxy and its companion, NGC 5195, show only subtle traces of an initial interaction. Others, such as the Mice, display the distorted shapes and long tidal tails that develop as gravity acts over longer periods of time. And still others, exemplified by the Antennae galaxies, are experiencing a full-blown impact. Here, the galaxies have lost much of their individual identities as gas clouds ram into one another and trigger a maelstrom of star birth.

Speaking of galaxy collisions, Hubble has verified that the Milky Way is not immune. Detailed observations of our large neighbor, the Andromeda Galaxy, show that it is on a collision course with our galaxy and will not merely pass closely. Over the next several billion years, these two behemoths will act out the same scenes now being performed by the Mice and Antennae.



Spectra made by Hubble and its sister Great Observatory, the Spitzer Space Telescope, helped nail down the atmospheric composition of this Saturn-mass exoplanet. The observations show the presence of water vapor and several other important compounds. *ASTRONOMY*: ROEN KELLY, AFTER NASA/ESA/G. BACON AND A. FEILD (STScI)/H. WAKEFORD (STScI/UNIV. OF EXETER)

It's not surprising that galaxies collide frequently. After all, Hubble observations show that the universe holds at least 100 billion galaxies. The number comes from the study of several "deep fields" the telescope has taken by turning its cameras on small areas of apparently empty sky and exposing for days at a time. Each deep field captures thousands of galaxies, from which astronomers can estimate the universe's total number.

To the dark side

Hubble's sensitive detectors only pick up the light coming from celestial objects. But clever scientists have used its observations to map out the darkness that dominates our universe. Dark matter is a mysterious material that radiates no light but whose gravity serves as the glue that holds individual galaxies and galaxy clusters together. It makes up 27 percent of the mass-energy content of the universe, more than five times what the normal matter that forms stars, planets, and people contributes.

The Tarantula Nebula (NGC 2070) in the Large Magellanic Cloud is the largest star-forming region in the known universe. Hubble, which resolved the central cluster (top center) into myriad stars, enables scientists to see objects in other galaxies with the clarity once possible only in our own. NASA/ESA/ESO/DANNY LACRUE

The space telescope has been able to map the distribution of cosmic dark matter despite its invisibility.

The Antennae galaxies, NGC 4038 and NGC 4039, are merging. This cosmic collision is giving birth to billions of new stars, most of which belong to bright blue star clusters. The large yellowish globes near the top and bottom of the image are the cores of the original galaxies. ESA/HUBBLE AND NASA

Tidal forces have pulled material from this pair of interacting spiral galaxies. The Mice sideswiped each other 160 million years ago and are now heading back for round two. Eventually, they will merge into a single elliptical galaxy. NASA/ESA/H. FORD (JHU)/G. ILLINGWORTH (UCSC/LO)/M. CLAMPIN (STScI)/G. HARTIG (STScI)/THE ACS SCIENCE TEAM

The Sunburst Arc Galaxy has been gravitationally lensed into at least 12 separate images that reside in four separate arcs around a foreground galaxy cluster chock full of dark matter. The lensed galaxy lies some 11 billion light-years from Earth, while the intervening cluster is 4.6 billion light-years away. NASA/ESA/E. RIVERA-THORSEN ET AL.

When astronomers look at large galaxy clusters, they often see wispy arcs and, sometimes, multiple images of background galaxies gravitationally lensed by material in the foreground cluster. These lenses magnify and distort light from more distant objects. Astronomers dissect Hubble's images and calculate where dark matter has to be to produce the observed distortions.

Although astronomers had seen hints that presaged many of Hubble's notable findings, the telescope's greatest discovery came out of the blue. Two research groups — one led by Saul Perlmutter of the University of California, Berkeley, and the other by Brian Schmidt at the Australian National University — were observing distant type Ia supernovae. These blasts occur in binary star systems in which a white dwarf pulls material from a red giant companion. When the white dwarf

reaches around 1.4 solar masses, it explodes.

Because type Ia supernovae arise from nearly identical progenitor stars, their peak luminosities match. So, once astronomers see how bright the supernova appears, they can calculate its distance. The teams found that the most distant type Ia explosions were fainter than their distances implied. The only way this made sense is if some force, dubbed "dark energy," is accelerating cosmic expansion. Planck showed that dark energy accounts for about 68 percent of the universe's mass-energy content, a sign that our universe will expand forever at an ever-increasing rate.

Despite Hubble's wealth of scientific accomplishments, the beauty of its images ranks among its chief legacies. Who isn't moved at seeing stars literally come to life in the glowing gas of a nearby nebula, watching the delicate tendrils of a dying star whose path the Sun will follow one day, or viewing the dramatic spiral structure of a nearby galaxy?

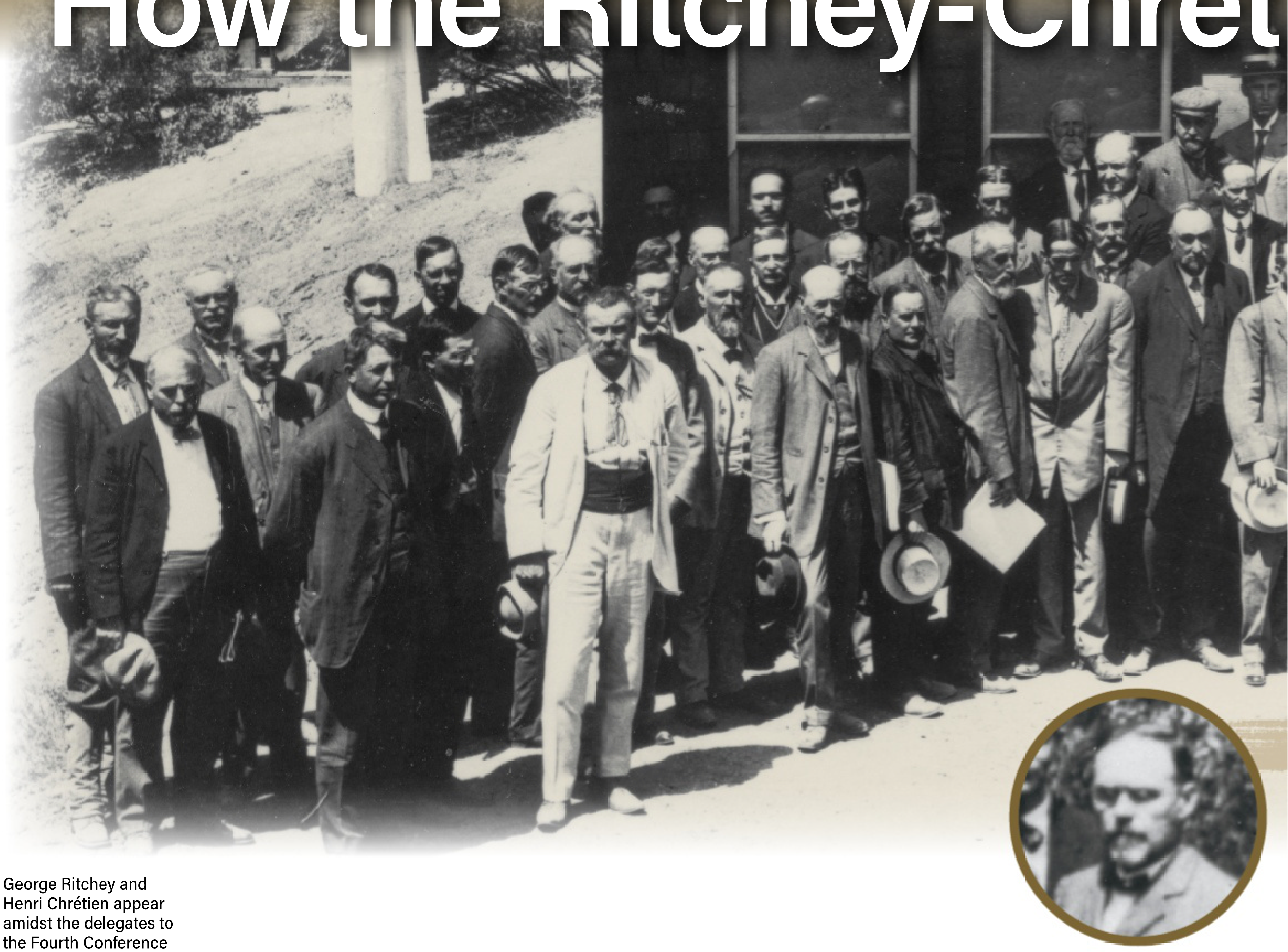
Nearly every image has its own charm, no doubt because it reflects the beauty inherent in nature. And, with any luck, the hits will keep coming for many more years.

The Hubble Ultra Deep Field captured some 10,000 galaxies in a tiny area of Fornax. The brightest galaxies here lie a billion light-years from Earth, while the faintest date back to a time several hundred million years after the Big Bang. NASA/ESA/S. BECKWITH (STScI)/THE HUDF TEAM

This image shows part of the original Hubble Deep Field after a type Ia supernova explosion. Hubble snapped the photo in 2002, seven years after the original image, revealing the bright red dot of Supernova 2002dd near center. At a distance of 8 billion light-years, this explosion helped shed light on when dark energy started to dominate the universe. NASA/J. BLAKESLEE (JHU)

Senior Editor **Richard Talcott** *has covered Hubble throughout the orbiting observatory's 30 years in space. His latest book is* Space Junk *(Ziga Media, 2019).*

How the Ritchey-Chrét



George Ritchey and Henri Chrétien appear amidst the delegates to the Fourth Conference of the International Union for Cooperation in Solar Research at the Mount Wilson Observatory in 1910. MOUNT WILSON AND PALOMAR OBSERVATORIES, COURTESY OF AIP EMILIO SEGRÈ VISUAL ARCHIVES

Just over 100 years ago, on October 31, 1919, George Willis Ritchey was fired from the Mount Wilson Observatory and ostracized by the American astronomical community. This dramatic event would ultimately set back by 50 years the development of the Ritchey-Chrétien telescope — the advanced optical system used in today's best research telescopes.

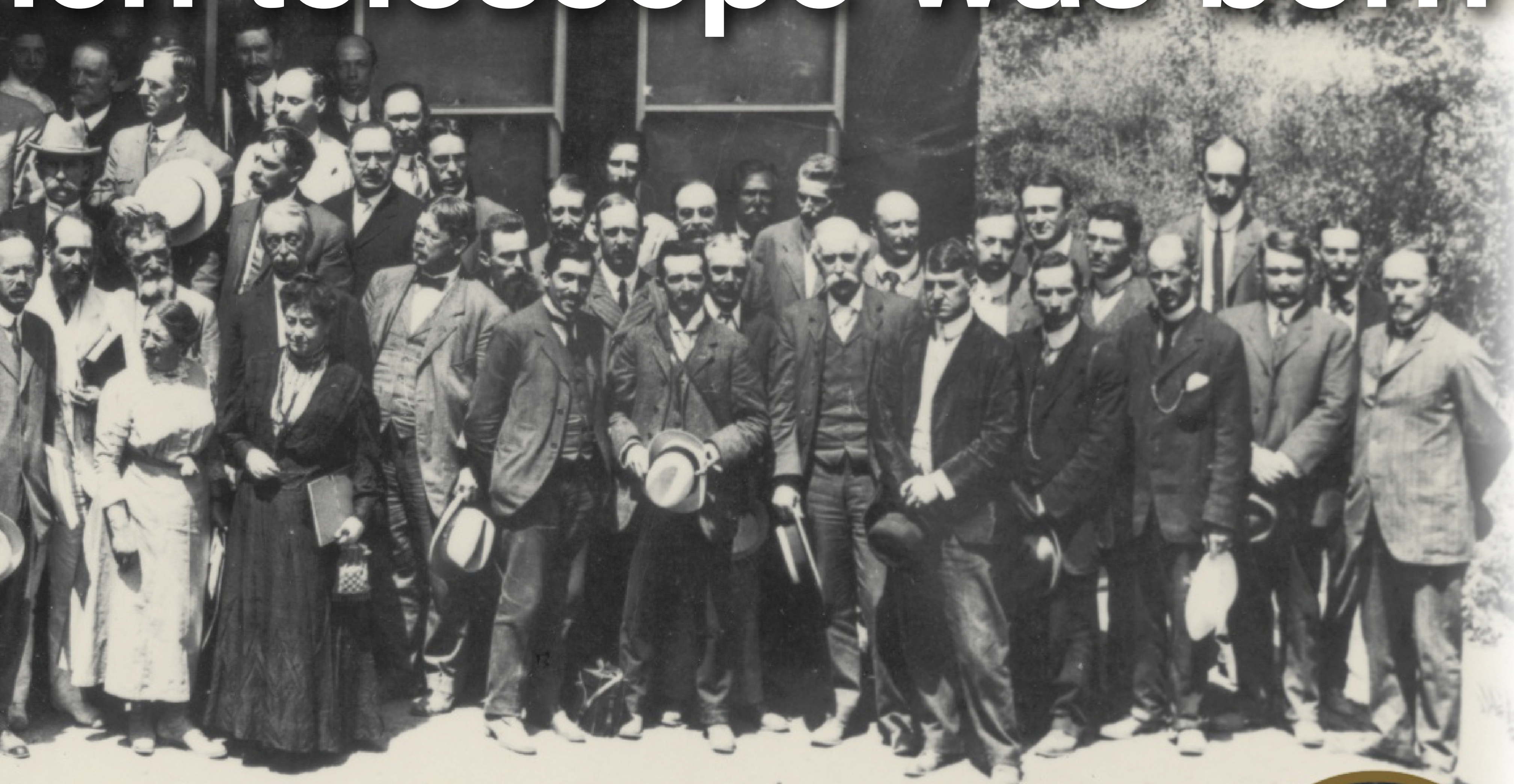
A fastidious man

Ritchey, the son and grandson of Irish immigrant furniture makers, had been trained in the art and craft of fine furniture design and construction. But he later discovered a love of optics — especially telescope optics — instrument design, and astrophotography. By the early 1900s, Ritchey had established himself as one of the world's leaders in shaping, polishing, and testing optics for use in telescopes.

Meticulous and methodical to a fault, Ritchey was also imperious and demanding of his shop assistants. He was one of the first to introduce standards for shop protocols: varnishing the walls and ceilings, keeping the floor wet during polishing, double sealing windows, and using air filtration systems to help eliminate dust. He developed most of the techniques he used for polishing and testing mirrors through years of careful work and detailed note-taking. His 1904 paper for the Smithsonian Institution, "On the Modern Reflecting Telescope, and the Making and Testing of Optical Mirrors," had become a must-read for any aspiring telescope optician. In it, Ritchey detailed the process by which he shaped a glass disk into a perfect section of a sphere and set about creating the curved shape for the mirror.

One of those inspired by Ritchey's writing was Henri Chrétien — a French astronomer, physicist, and optical engineer. Chrétien came to Mount Wilson as a visiting researcher from the Nice Observatory in France in 1909. There he met Ritchey, and the two

ien telescope was born



George Ritchey had great vision and skill. Henri Chrétien was a brilliant astronomer and optical engineer. Together, they created one of today's best telescope designs.

BY RON VOLLER

worked on direct photography with Mount Wilson's newly completed 60-inch telescope. Chrétien was a brilliant optician in his own right and was impressed by the incredible performance and optics of the telescope, which was Ritchey's latest and greatest achievement. Ritchey was equally impressed with Chrétien's knowledge, skill, and creativity as an engineer. This mutual respect and admiration led them to correspond regularly after Chrétien's return to Paris a year later.

New curves

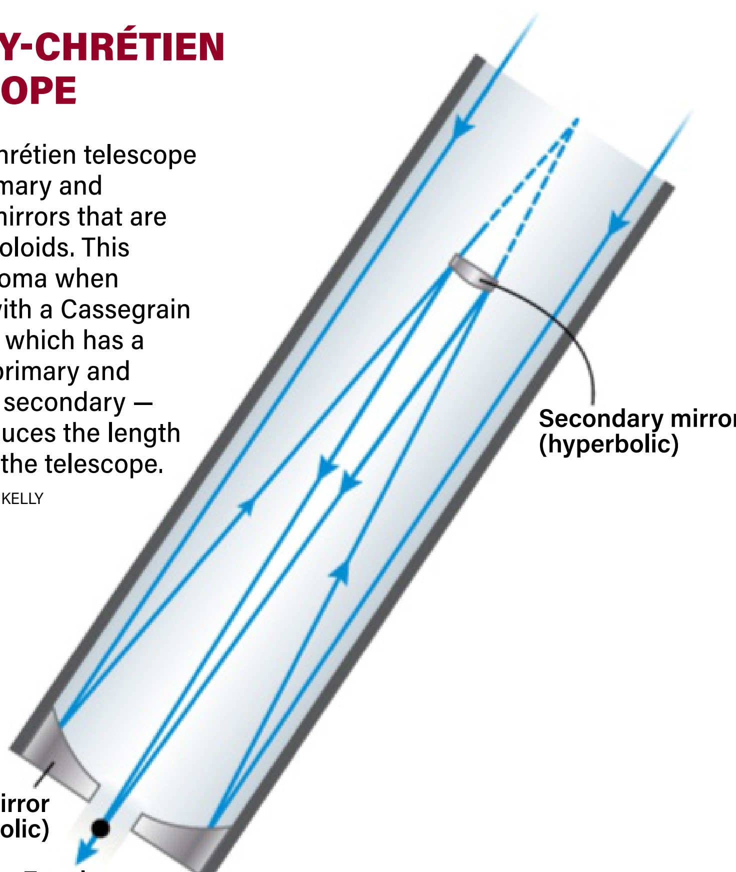
At about that time, Ritchey was designing the 100-inch Hooker Telescope at Mount Wilson, which he and the observatory's director, George Ellery Hale, assumed would employ a paraboloidal primary mirror with an array of flat, parabolic, and hyperbolic secondary mirrors.

But while comparing photos taken with the 60-inch reflector, which had a parabolic primary mirror, Ritchey noticed that the images taken using a

RITCHEY-CHRÉTIEN TELESCOPE

A Ritchey-Chrétien telescope employs primary and secondary mirrors that are both hyperboloids. This eliminates coma when compared with a Cassegrain telescope — which has a paraboloid primary and hyperboloid secondary — and also reduces the length required for the telescope.

ASTRONOMY: ROEN KELLY



George Ritchey (second from the right) sits with fellow astronomers, including George Ellery Hale (fifth from the right, seated on the high wall behind the two men on the lower steps), in front of Yerkes Observatory in Williams Bay, Wisconsin, in August 1898. YERKES OBSERVATORY, UNIVERSITY OF CHICAGO, COURTESY OF AIP EMILIO SEGRÈ VISUAL ARCHIVES AND SPECIAL COLLECTIONS RESEARCH CENTER, UNIVERSITY OF CHICAGO LIBRARY

hyperbolic secondary mirror at the Cassegrain focus were sharper than those taken with the same mirror at either the Newtonian or prime focus. The longer focal ratio of the scope's Cassegrain focus reduced comatic aberration, or coma. (Focal ratio is a telescope's focal length divided by the size of its aperture; smaller focal ratios are considered faster.)

Coma affects all parabolic mirrors by stretching a star's image as the object moves off-axis. The image may be perfect at the center of the field, but closer to the edge, it becomes distorted. This necessarily limits the size of high-quality pictures taken using parabolic systems.

Ritchey wondered whether a more refined hyperboloid secondary mirror might reduce — or perhaps even eliminate — coma altogether. He wrote to Chrétien in Paris to see if he could come up with a workable solution mathematically. Chrétien determined that a highly specialized hyperboloid primary and secondary mirror, one concave (curved inward) and the other convex (curved outward), could reduce coma to zero.

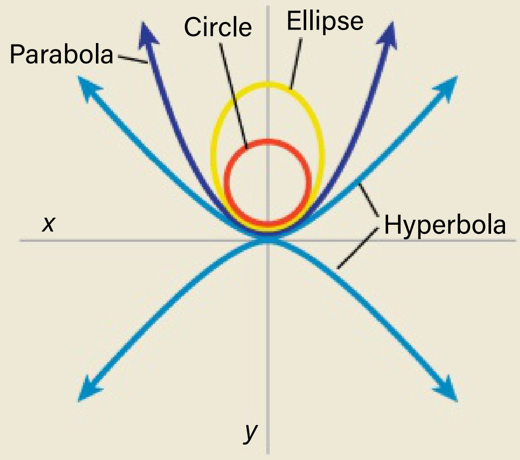
When he received the news, Ritchey was delighted at the possibilities their "new curves" represented and began to conceive of the 100-inch telescope as the world's first "Ritchey-Chrétien" telescope. An instrument of this type would create perfect images everywhere without the need for a collimating lens, which then-current reflectors required to "flatten" the view they produced for better image quality. The telescope's Cassegrain setup would make possible a primary mirror with a fast focal ratio, reducing the length of the telescope's tube. This would give the telescope a more compact profile, enabling a smaller dome and a compact, lighter frame and mounting system, thus lowering overall building costs. The idea was as ingenious as it was prescient.

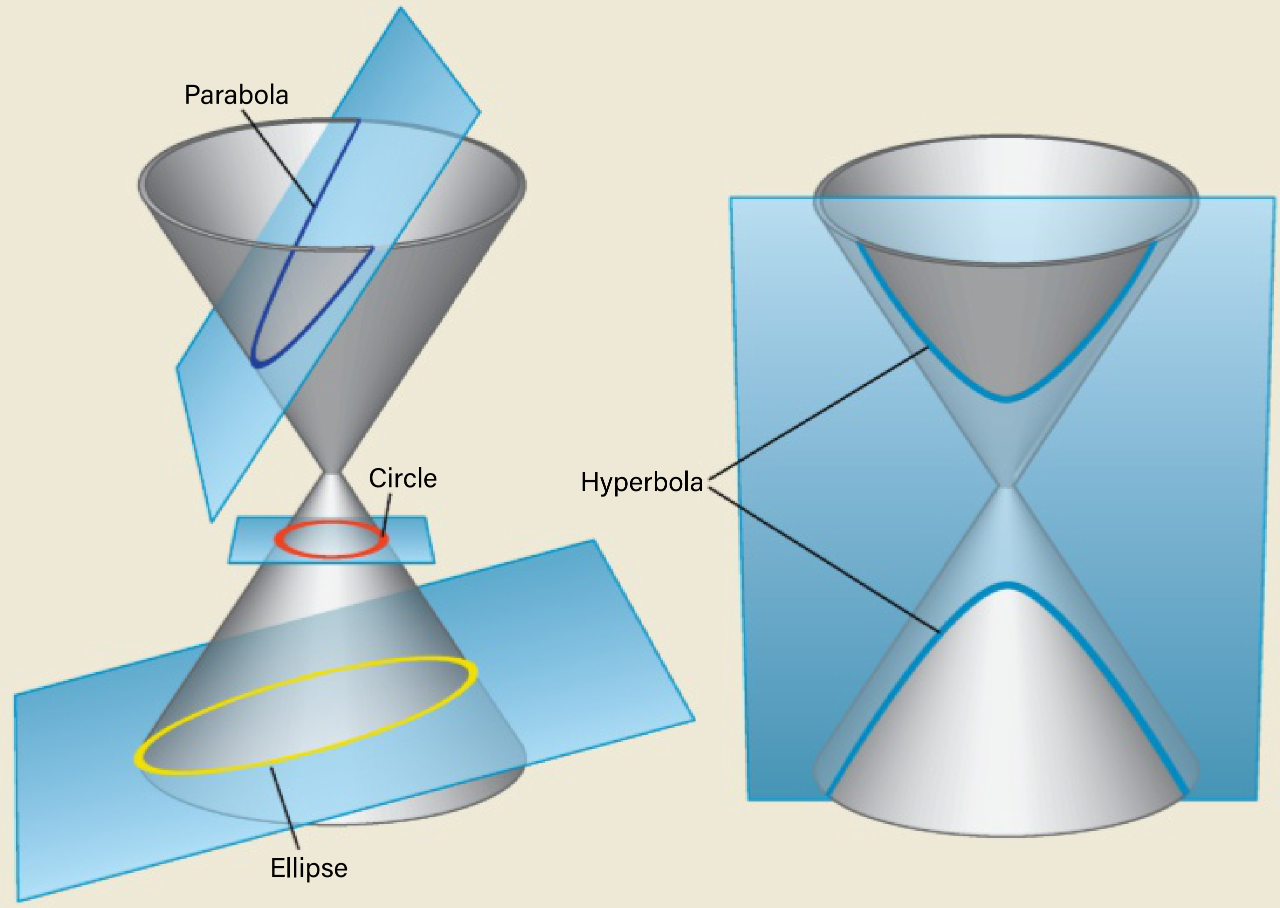
Old vs. new

Ritchey immediately set about trying to convince Hale and Mount Wilson assistant director Walter Adams that the 100-inch should use the new curves — a move that would ultimately prove to be Ritchey's undoing.

By 1910, the 100-inch project was woefully behind schedule and over budget. With funds from the trust created by hardware magnate John D. Hooker, for whom the telescope was named, running out, and Hooker's increased anxiety and frustration at the delays, Hale went into emergency mode.

Meanwhile, Ritchey continued to assert that the telescope ought to be a Ritchey-Chrétien system, rather than the standard parabolic Cassegrain system.



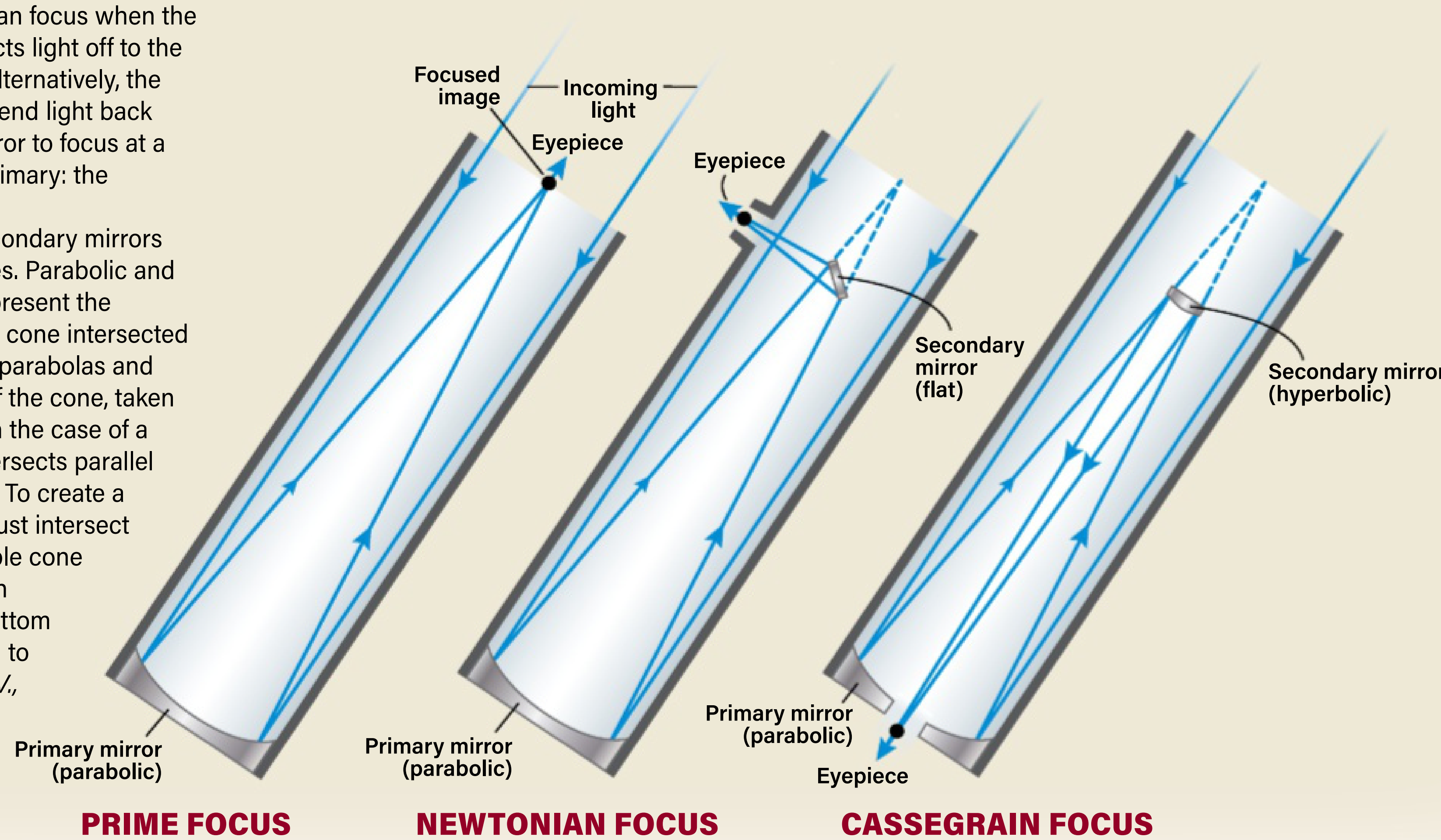


Parabolas and hyperbolas are conic sections, which mean they are curves created by taking slices through a cone. A parabola results from the intersection of a plane parallel to one side of the cone. Inserting a plane at a steeper angle creates a hyperbola. *ASTRONOMY*: ROEN KELLY

TELESCOPES AND MIRRORS

In a reflecting telescope, the prime focus is the point where light rays bouncing off the primary mirror create a clear image in front of the primary. But this is typically an inconvenient place to focus light. A secondary mirror, placed in the path of light reflected from the primary mirror, can focus the image elsewhere. Light focuses at the Newtonian focus when the secondary mirror deflects light off to the side of the telescope. Alternatively, the secondary mirror can send light back toward the primary mirror to focus at a point just behind the primary: the Cassegrain focus.

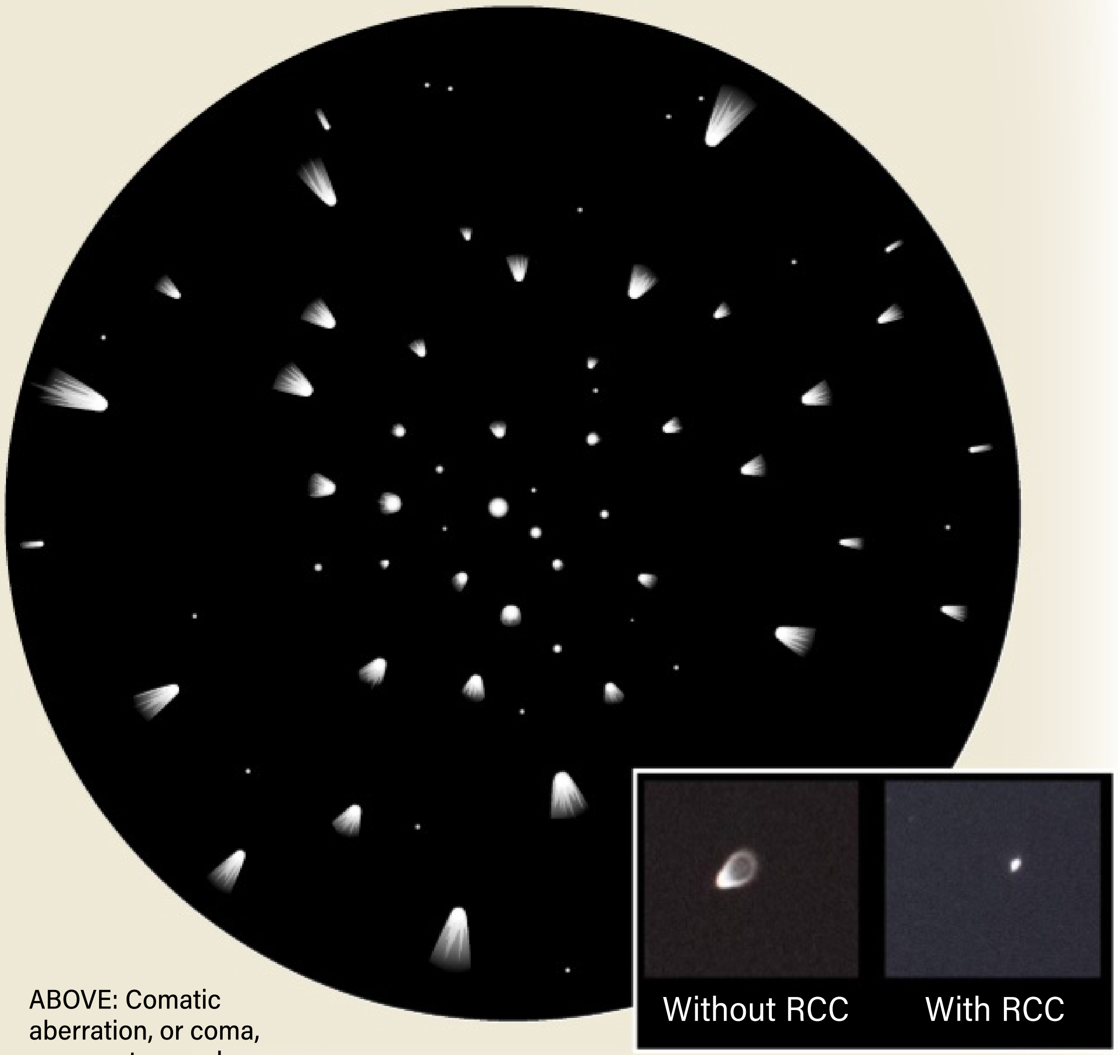
The primary and secondary mirrors can have various shapes. Parabolic and hyperbolic surfaces represent the geometric sections of a cone intersected by a plane. In essence, parabolas and hyperbolas are slices of the cone, taken from different places. In the case of a parabola, the plane intersects parallel to one side of the cone. To create a hyperbola, the plane must intersect both surfaces of a double cone at a steeper angle, often perpendicular to the bottom of the cone and parallel to its axis of rotation. — *R.V., Alison Klesman*



As he, Hale, and Adams argued over the proper design, Ritchey, who had befriended Hooker and gained his confidence, quietly made his case in no uncertain terms. He had come to the opinion that Hale and Adams had no idea what they were talking about.

Hale later learned of Ritchey's circumvention of his authority and promptly demoted him from lead on the 100-inch project, relegating him to the optical shop where he would remain until the 100-inch primary mirror was finished, polished, and tested for use in the telescope. The highly persuasive director then convinced Hooker that the original parabolic design was perfect for his new telescope. Hale's reputation as a scientist, instrument designer, and observatory builder doomed Ritchey, who lacked the poise and power of persuasion of the Mount Wilson director. Hooker soon relented and died not long after, leaving Ritchey to his fate. He had bitten the hand that fed him and his days at Mount Wilson were numbered.

When Ritchey was forced to depart Mount Wilson in the fall of 1919 — just as the likes of Edwin Hubble and Milton Humason were beginning highly profitable



ABOVE: Comatic aberration, or coma, causes stars and other objects at the edge of a telescope's field to appear distorted. *ASTRONOMY*: ROEN KELLY

INSET: This image, taken with an f/3.9 Newtonian telescope, shows coma affecting a star (left), as well as the same star after correction with a Baader Rowe Coma Corrector (RCC). Similarly, Ritchey's and Chrétien's "new curves" eliminated coma in Cassegrain telescopes by using hyperbolic primary and secondary mirrors. RAWASTRODATA (WIKIMEDIA COMMONS)

RIGHT: Ritchey completed a 40-inch Ritchey-Chrétien telescope — the largest built during his lifetime — for the U.S. Naval Observatory (USNO) in 1934. The telescope went into service the following year. Initially installed in Washington, D.C., the telescope now resides at the USNO's Flagstaff, Arizona, location. P. SHANKLAND

associations with the organization — he was determined to create his own telescope-building company.

But Hale and Adams had other ideas. Their 100-inch telescope would not be upstaged by any newly designed creation, especially one by their disgraced former associate. Hale used his position as observatory director to set about ruining Ritchey's reputation.

Soon, Ritchey realized he would never again work in any capacity in astronomy in the U.S. His ego, his arrogance, and his willful insubordination over the 100-inch had gotten him censured from astronomical work in the country.

A new start

Fortunately, Ritchey had friends in Europe. Five years after leaving Mount Wilson, he sailed for France at the invitation of Chrétien and the Paris Observatory, who were planning a 104-inch telescope. By this time, Chrétien was a professor at the Institut d'Optique and beginning development of the hypergonar lens system, which won him an Academy Award of Merit at the 26th Academy Awards after it was used to create the CinemaScope widescreen film process. (He is the only astronomer to win an Academy Award.)

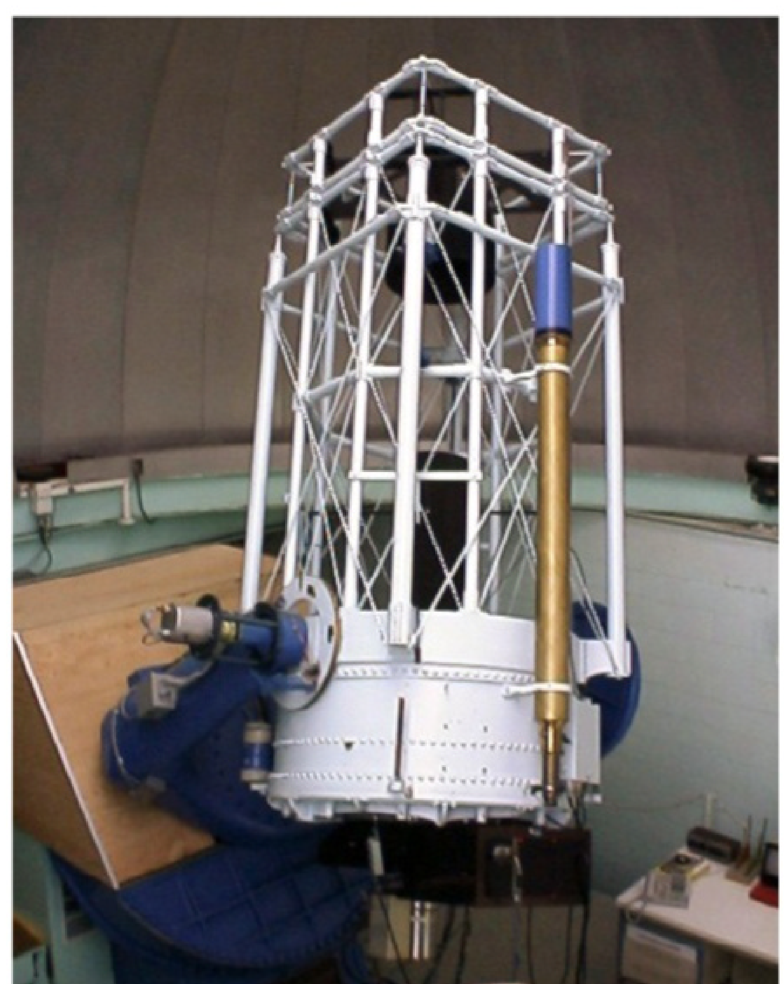
The French astronomical community anxiously awaited the arrival of the visionary optician and instrument maker. On April 8, 1924 — about a week after his arrival in Paris — Ritchey was awarded the Janssen Medal by the French Academy of Sciences for his work on astronomical instruments. It was an auspicious beginning, but relations soured from there.

The Paris telescope's benefactor, Assan Farid Dina, thought the design should employ the same paraboloidal primary mirror as its slightly smaller cousin in California, while Chrétien (and others) were eager to design it as the first large Ritchey-Chrétien telescope. Inexplicably, after some deliberation, Ritchey decided on a 5- or 6-meter (197 to 236 inches) telescope, incorporating his newly patented cellular primary mirror design as a Ritchey-Chrétien hyperboloid.

The telescope was never built. Long on vision, ambition, and skill, but short on tact, charisma, and charm, the 59-year-old Ritchey began slowly to break down the welcome extended to him by the French astronomical community. He never bothered to learn French and failed as a project manager and planner, bouncing from one position to the next as his colleagues tried in vain to find a position that suited his incredible talent, but would rein in his budget-sapping ambition and perfectionism.

Both Ritchey and Chrétien attempted several times to earn a contract to build a Ritchey-Chrétien telescope, either in Europe or the U.S. But fears over the effectiveness of the mirror configuration — fomented as they were by Hale and others — and Ritchey's own beleaguered reputation scuttled these attempts as larger and more reputable firms earned contracts for proven telescope configurations.

It was the U.S. Naval Observatory that finally gave Ritchey the opportunity to build a Ritchey-Chrétien telescope sized to show off its finer attributes. In 1930, Ritchey returned to the U.S.; soon after, the Naval Observatory commissioned a 40-inch Ritchey-Chrétien reflector by the aging



telescope maker. The French were more than happy to bid him adieu.

Ritchey's entire career in France had yielded only a 0.5-meter Ritchey-Chrétien telescope mounted on a wooden frame. The 40-inch telescope he designed and built for the Naval Observatory, which went into service in 1935, was Ritchey's masterpiece, nearly 25 years in the making. The only trouble was that it had been built and installed on the observatory grounds in Washington, D.C. Imagine the *Mona Lisa* hanging on the wall of a barbershop. The site just wasn't very good.

A long legacy

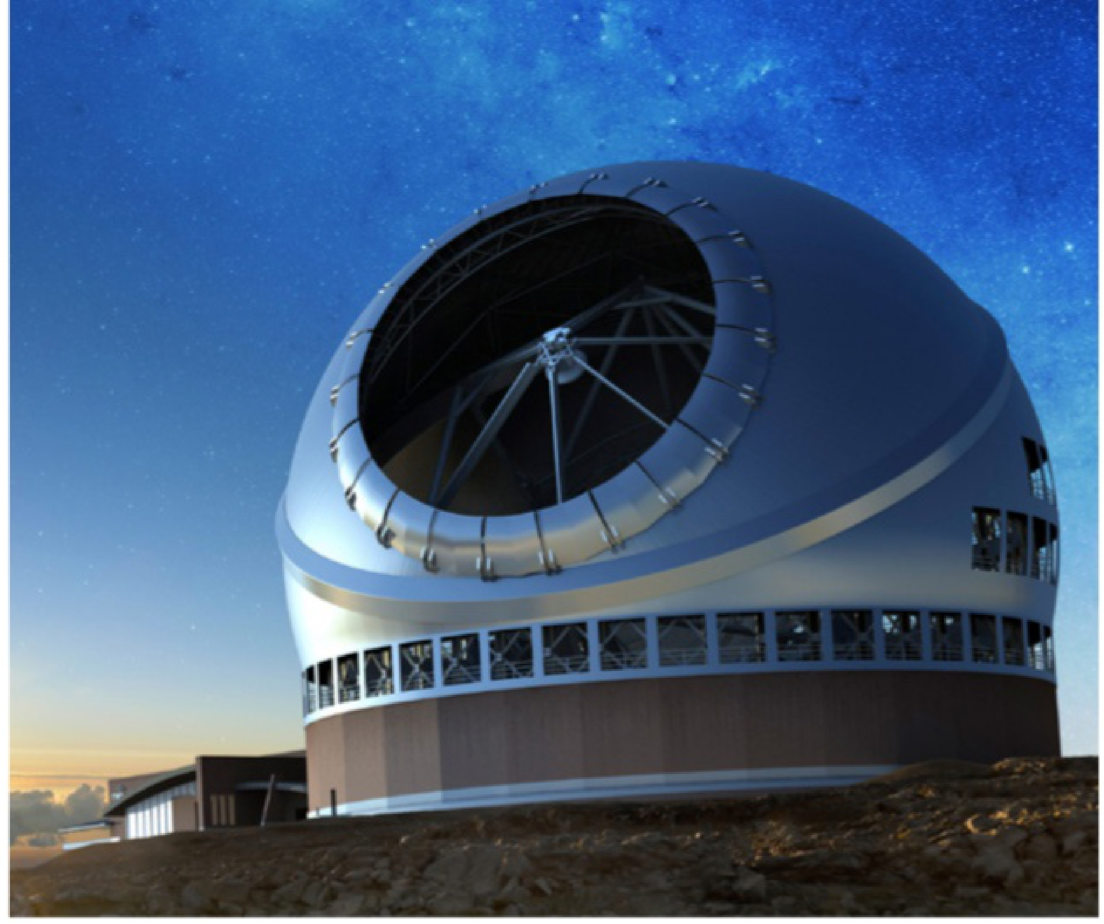
Ritchey died in November 1945 at age 80. The 40-inch Naval Observatory telescope, now the ancestor of all large modern research telescopes, was moved in 1955 to a more optimal location near Lowell Observatory in Flagstaff, Arizona. There, the likes of John S. Hall and Arthur Hoag exploited its superior resolving capability. The second large Ritchey-Chrétien reflector, the 84-inch telescope at Kitt Peak National Observatory, was completed in the spring of 1960, half a century after the first seed of the idea took root in the fertile mind of its creator. From there, the Ritchey-Chrétien system swept the world.

Ritchey was probably the greatest visionary telescope maker of all time. In addition to the Ritchey-Chrétien telescope, his ideas included cellular mirrors, lightweight mirrors that respond rapidly to temperature changes, internal dome temperature control, thermal distortion-reducing telescope mountings, and making rapid focus changes to optimize fluctuating seeing conditions. These concepts have now been used in nearly every large land-based and space telescope since the completion of the 200-inch Hale reflector — the last to use a parabolic primary mirror — at Palomar Mountain in 1948. The groundbreaking and historic Hubble Space Telescope, as well as future supergiants like the Thirty Meter Telescope in Hawaii, employ Ritchey-Chrétien systems.

Had he been able to suppress his desire and ambition, and fallen in line during the 100-inch telescope's development in the 1910s, Ritchey might have had the opportunity to develop his "new curves" system in smaller telescopes first, working out the kinks along the way. In such a world, the Hale Telescope could have been the first large Ritchey-Chrétien telescope. This would have benefited Hubble, Walter Baade, Allan Sandage, and other cosmologists. But Ritchey's insubordination and Hale's ignorance sealed the 200-inch's fate 30 years before it was completed.

By contrast, Chrétien, who died in 1956 at age 77, was highly regarded during his lifetime and rewarded handsomely for his contributions to the field of optics. In addition to his Academy Award and Prix Janssen medal, he received the Valz Prize from the French Academy of Sciences. The American Astronomical Society's Chrétien International Research Grant, which was created in 1982 to award up to $20,000 each year in support of international observational astronomy, was named in his honor.

Ritchey never lived to see his optical and instrument designs "proclaim the glory of God," as he frequently wrote. Instead, his final years were spent writing draft after draft of books about the astronomical equipment he dreamed would one day convey the true nature of the heavens. The fact that he was never able to find a publisher for these volumes was perhaps the final insult in a life dedicated to designing the most advanced astronomical equipment ever conceived. His legacy is written in the incredible cosmological advancements his signature telescope design has allowed and will continue to generate well into the future.



ABOVE: The Thirty Meter Telescope currently under construction (shown completed in this artist's concept) will employ a Ritchey-Chrétien design to achieve the sharpest images possible. TMT INTERNATIONAL OBSERVATORY

LEFT: The 200-inch Hale Telescope, housed at the Palomar Observatory, was the last major astronomical workhorse telescope to use the Cassegrain design. CALTECH/PALOMAR OBSERVATORY

Ron Voller *is a writer of science history based in New York City. His forthcoming book,* Companion Stars: The Misfits Hubble and Humason Discover the Big Bang, *is due for publication in 2020.*

Visible to the naked eye
Visible with binoculars
Visible with a telescope

THE SOLAR SYSTEM'S CHANGING LANDSCAPE AS IT APPEARS IN EARTH'S SKY.

BY MARTIN RATCLIFFE AND ALISTER LING

Venus dazzles on March evenings, outshining the night sky's brightest star, Sirius, by 15 times. In this November 2018 scene, the planet dominated the predawn sky. ALAN DYER

MARCH 2020

Venus sidles up to Uranus

As we enter the waning weeks of winter, Venus dominates the evening sky for more than three hours after sunset. And because of the prominence of the planet, March is a great time to use Venus as your guide to spot Uranus, especially if you've never seen it before. The pair stand close together for a couple of days early in the month. However, the main planetary focus is in the morning sky. Get up before dawn to spot two planetary conjunctions and three great planets — Mars, Jupiter, and Saturn — glowing brightly in the southeastern sky. It's a stunning collection that only grows more striking when the Moon briefly joins the party.

Let's start our tour of the night sky in the early evening March 1. A quick look high in the west reveals a brilliant planet, **Venus**, along with a waxing crescent Moon in Taurus the Bull. Venus shines at a glittery magnitude of –4.3. And during the first few days of March, the world marches into southern Aries, where **Uranus** currently resides.

Nearby Venus and distant Uranus stand just a scant 2.2° apart March 7 and 8. Due to their proximity, it's much easier to pick out the dim magnitude 5.9 Uranus from what's usually a rather bland star field. On March 7, grab binoculars to spy Uranus southeast of Venus. During the evening, the ice giant sits near Venus, but there's another field star closer to and in the same direction as the bright planet. Scan about twice the star's distance from Venus to home in on Uranus, which is located about 1.9 billion miles away, or about 24 times farther away than Venus.

On March 8, a pair of 7th-magnitude stars linger about 1.2° to the lower left of Venus. Travel twice that distance in the same direction to track down the brighter Uranus.

Throughout the remainder of March, Uranus trudges about 1° eastward. Venus, in comparison, jumps through Aries with aplomb. The nearby world is joined by a waxing Moon on March 27 and 28, when the beautiful pairing hovers just below the V-shaped

Venus rules the evening sky

The inner planet stands high in the western sky after sunset all month, but peaks at greatest elongation March 24. ALL ILLUSTRATIONS: *ASTRONOMY*: ROEN KELLY

OBSERVING HIGHLIGHT

MARS sits 42' south of Jupiter the morning of March 20. Mars' 0.9-magnitude orange glow contrasts nicely with Jupiter's magnitude –2.1 yellowish light.

Hyades star cluster. By March 29, the Moon, the Hyades, the Pleiades, and Venus all lie in a 17°-wide circle as Venus crosses into Taurus. Venus ends the month less than 3° from the sparkling Pleiades star cluster (M45) in Taurus and will grow closer still in the first few days of April.

If you target Venus with your telescope during March, you won't be disappointed. You'll see the planet's Earth-facing hemisphere morph from a plump 62 percent lit to just 47 percent lit over the course of a month. Over the same span of time, Venus' disk goes from 19" to 26" across. Though a true half-lit Venus occurs March 26, due to Schröter's effect, you can observe the split-view up to six days earlier for eastern elongations. Take a look and see what you think. Thanks to lighting effects along the terminator of Venus and the scattering of light in our atmosphere, determining the planet's exact 50 percent phase is a difficult challenge.

In the predawn sky March 1, **Mars**, **Jupiter**, and **Saturn** span 19° along the ecliptic. The trio put on a stunning show all month as Mars cruises past both giant planets. From mid-northern latitudes, you can target the worlds above the southeastern horizon between 5:30 A.M. and 6:15 A.M. local

— *Continued on page 42*

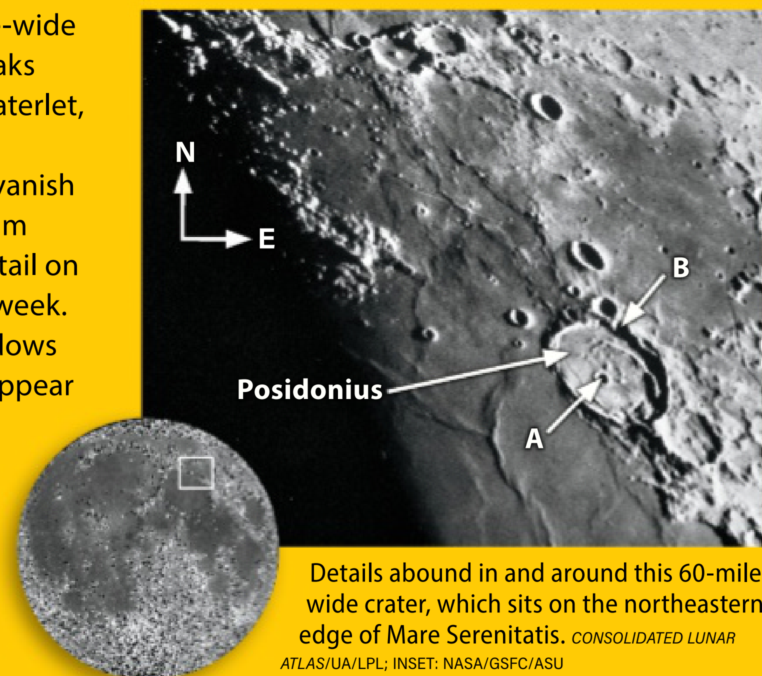
RISING MOON | A fortnight of features

PACKED WITH DETAIL, the large crater Posidonius is near the top of most lunar lovers' lists. The lava-filled interior of this 60-mile-wide ancient impact sports cracks, jumbled peaks poking up from the floor, an off-center craterlet, and bright segments of slumped walls.

Unlike most craters, which seemingly vanish at Full Moon, Posidonius boasts a bright rim with a cream pie face; one that's full of detail on the inside and lasts through March's first week. Changes in terrain heights from long shadows that were obvious the previous week disappear under a high Sun. Instead, the variety of gray we see comes from the differences in albedo, or reflectivity. The darker lava on the flooded floor contrasts nicely against the brighter specks left by small impacts and the highlight of a long arc of slumped terrace that faces upward.

When the Sun sets over this region late on the evening of March 13, the shadows and highlights will be reversed compared with the image here, getting longer as the minutes pass. This is a prime time to track how lunar features become increasingly exaggerated, but a close second is watching them march into lunar day when the Moon is an evening crescent on the 29th. The raised rim with its companion eyeline-like shadow is striking.

Posidonius



Details abound in and around this 60-mile-wide crater, which sits on the northeastern edge of Mare Serenitatis. CONSOLIDATED LUNAR ATLAS/UA/LPL; INSET: NASA/GSFC/ASU

Easily confused with Poseidon, the Greek god of the sea, Posidonius is actually named after a Greek astronomer and philosopher who lived around 100 B.C. Look for Posidonius in the north-east quadrant of the Moon. Posidonius B is a noticeable 9-mile-wide fresh impact on the northeast rim, while the slightly smaller crater A has the sharp edges of youth. Age is relative, since a fresh feature is 100 million years old.

METEOR WATCH | Glimpse the solar system's dim glow

Spot a fleeting flash

MARCH IS THE PERFECT MONTH to glimpse isolated meteors not associated with any known showers. And even if you don't spot any random streaks, March is still ideal for capturing views of zodiacal light. This faint glow is the result of fine debris — left by eons of long-since-faded ancient comets — littering the ecliptic plane. Once twilight has passed, look for a cone-shaped light above the western horizon. In order to spot it, you'll need a dark and moonless sky. The feeble glimmer is aligned with Earth's orbital plane, and passes through Pisces, Aries, and Taurus. Use peripheral vision to scan from left to right to spot the darker skies on either side of the weak glow. With a Full Moon on March 9, the best times to view zodiacal light are after the second week of the month before moonrise.

Sporadic meteors can show up without warning, like this one captured from Yosemite National Park in August 2013. TONY ROWELL

STAR DOME

HOW TO USE THIS MAP

This map portrays the sky as seen near 35° north latitude. Located inside the border are the cardinal directions and their intermediate points. To find stars, hold the map overhead and orient it so one of the labels matches the direction you're facing. The stars above the map's horizon now match what's in the sky.

The all-sky map shows how the sky looks at:

10 P.M. March 1
10 P.M. March 15
9 P.M. March 31

Planets are shown at midmonth

MAP SYMBOLS

- Open cluster
- Globular cluster
- Diffuse nebula
- Planetary nebula
- Galaxy

STAR MAGNITUDES

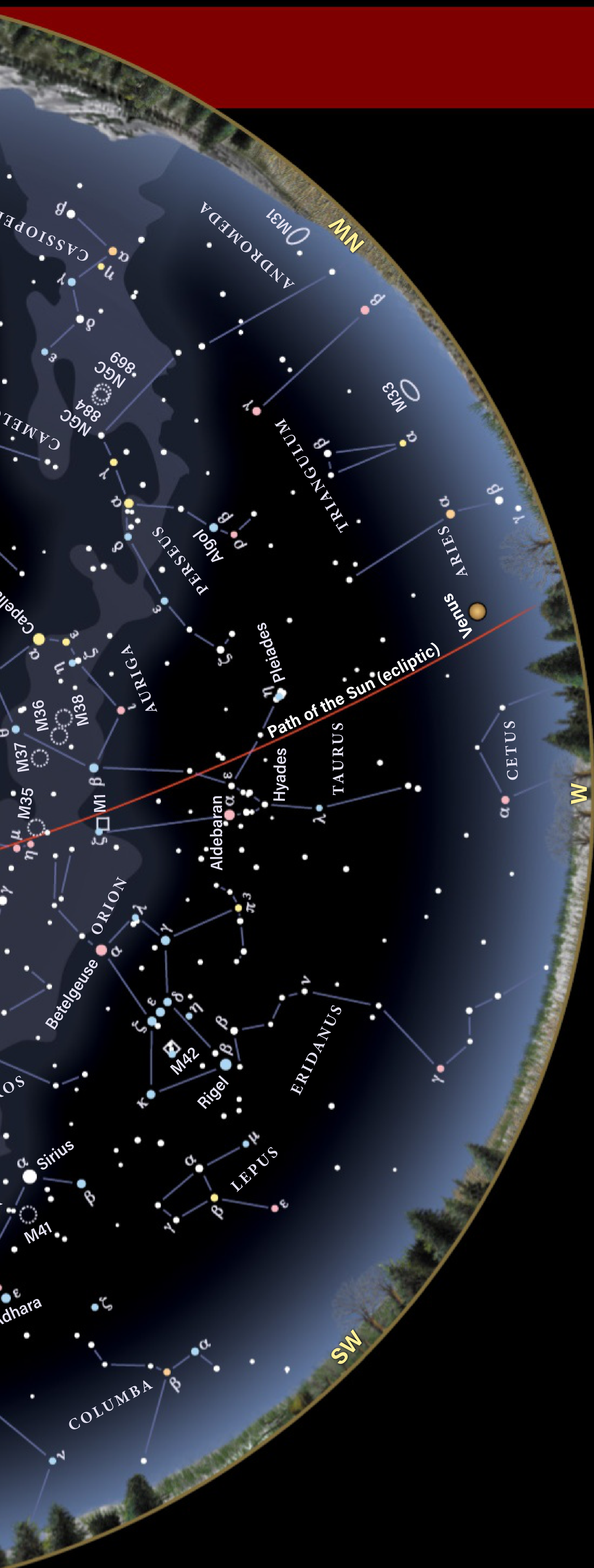
- Sirius
- 0.0
- 1.0
- 2.0
- 3.0
- 4.0
- 5.0

STAR COLORS

A star's color depends on its surface temperature.

- The hottest stars shine blue
- Slightly cooler stars appear white
- Intermediate stars (like the Sun) glow yellow
- Lower-temperature stars appear orange
- The coolest stars glow red
- Fainter stars can't excite our eyes' color receptors, so they appear white unless you use optical aid to gather more light

BEGINNERS: WATCH A VIDEO ABOUT HOW TO READ A STAR CHART AT **www.Astronomy.com/starchart.**



MARCH 2020

SUN.	MON.	TUES.	WED.	THURS.	FRI.	SAT.
1	2	3	4	5	6	7
8	9	10	11	12	13	14
15	16	17	18	19	20	21
22	23	24	25	26	27	28
29	30	31				

ILLUSTRATIONS BY *ASTRONOMY*: ROEN KELLY

Note: Moon phases in the calendar vary in size due to the distance from Earth and are shown at 0h Universal Time.

CALENDAR OF EVENTS

1 The Moon passes 0.1° south of asteroid Vesta, 1 A.M. EST

2 First Quarter Moon occurs at 2:57 P.M. EST

8 Neptune is in conjunction with the Sun, 8 A.M. EDT

9 Mercury is stationary, 4 A.M. EDT

Venus passes 2° north of Uranus, 11 A.M. EDT

Full Moon occurs at 1:48 P.M. EDT

10 The Moon is at perigee (221,905 miles from Earth), 2:30 A.M. EDT

14 Asteroid Euterpe is at opposition, 2 P.M. EDT

16 Last Quarter Moon occurs at 5:34 A.M. EDT

18 The Moon passes 0.7° south of Mars, 4 A.M. EDT

The Moon passes 1.5° south of Jupiter, 6 A.M. EDT

The Moon passes 0.9° south of Pluto, 11 A.M. EDT

The Moon passes 2° south of Saturn, 8 P.M. EDT

19 Vernal equinox occurs at 11:50 P.M. EDT

20 Mars passes 0.7° south of Jupiter, 2 A.M. EDT

21 The Moon passes 4° south of Mercury, 2 P.M. EDT

23 Mercury is at greatest western elongation (28°), 10 P.M. EDT

24 New Moon occurs at 5:28 A.M. EDT

The Moon is at apogee (252,707 miles from Earth), 11:23 A.M. EDT

Venus is at greatest eastern elongation (46°), 6 P.M. EDT

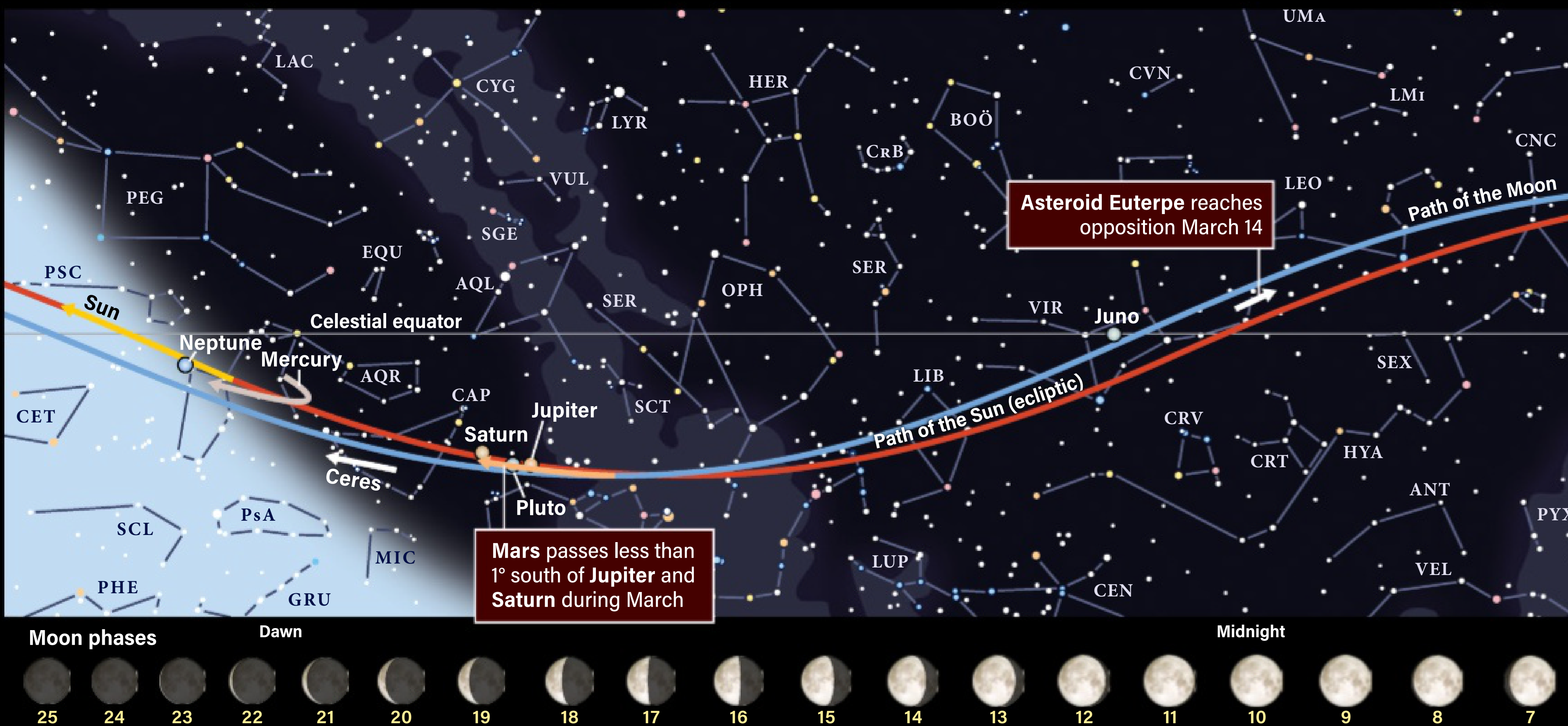
26 The Moon passes 4° south of Uranus, 5 P.M. EDT

28 The Moon passes 7° south of Venus, 7 A.M. EDT

29 The Moon passes 0.2° south of asteroid Vesta, 3 A.M. EDT

31 Mars passes 0.9° south of Saturn, 7 A.M. EDT

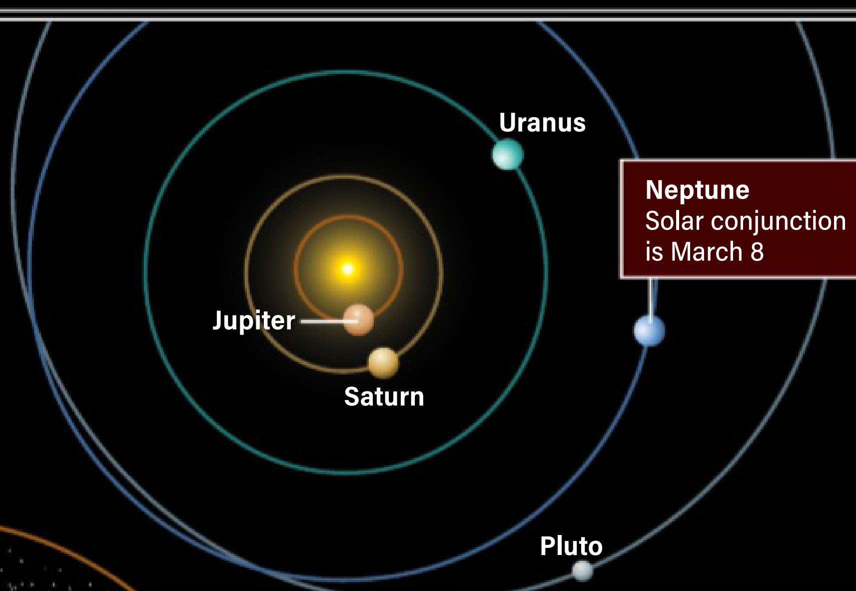
PATHS OF THE PLANETS

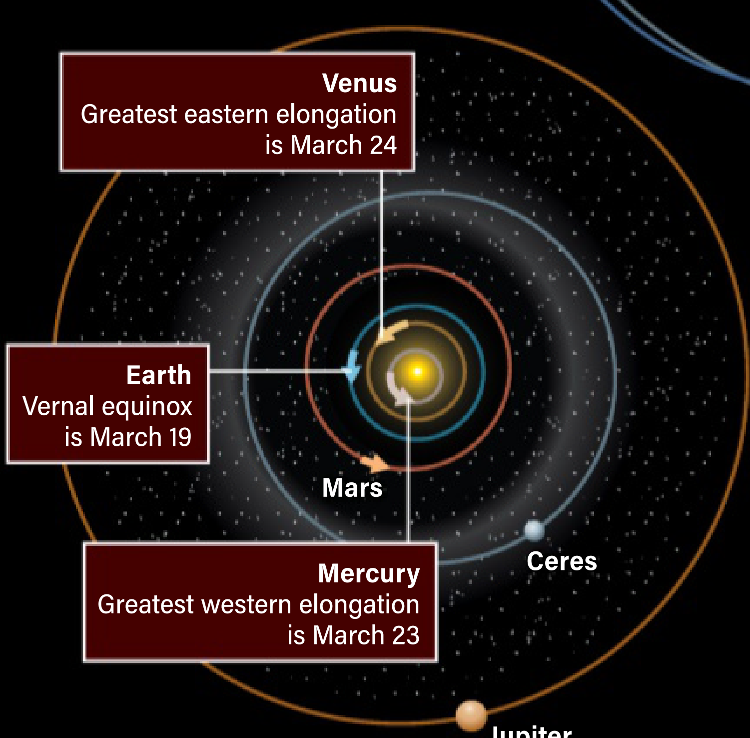


To locate the Moon in the sky, draw a line from the phase shown for the day straight up to the curved blue line.

THE PLANETS IN THEIR ORBITS

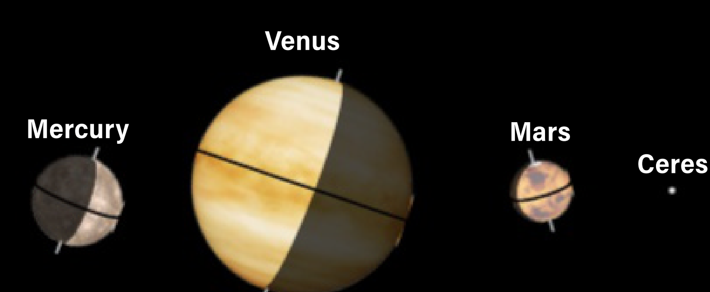
Arrows show the inner planets' monthly motions and dots depict the outer planets' positions at midmonth from high above their orbits.





THE PLANETS IN THE SKY

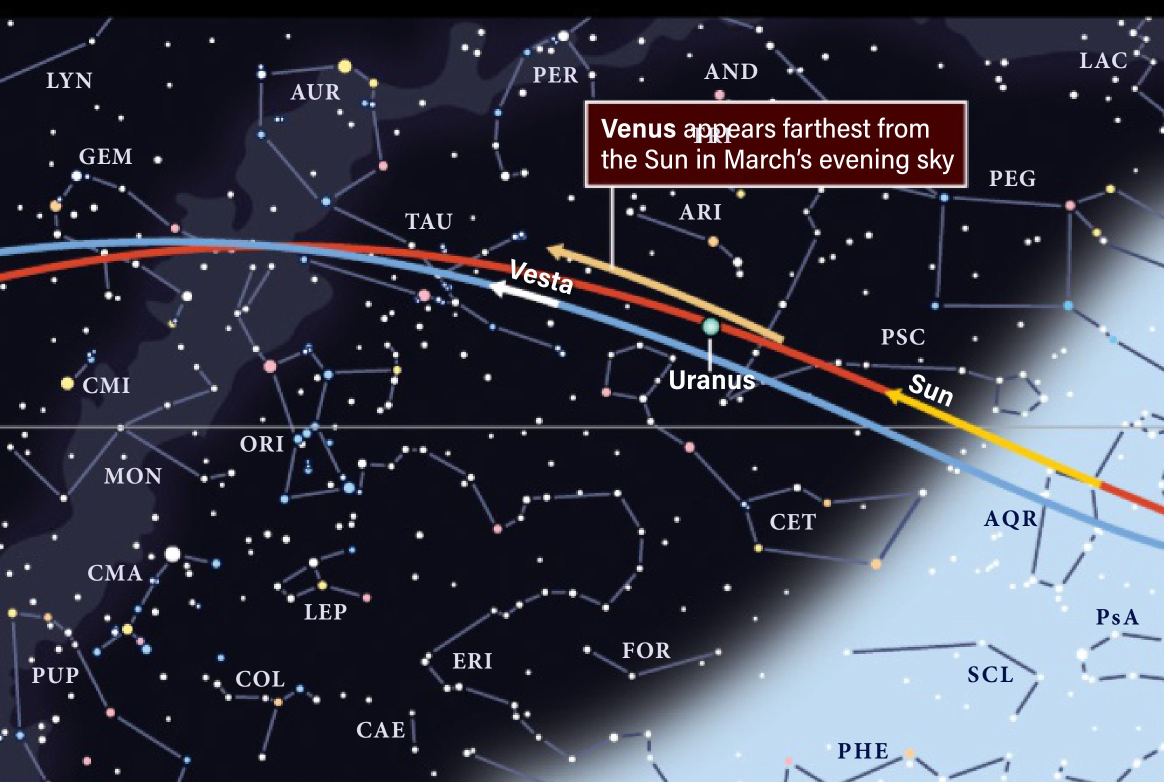
These illustrations show the size, phase, and orientation of each planet and the two brightest dwarf planets at 0h UT for the dates in the data table at bottom. South is at the top to match the view through a telescope.



PLANETS	MERCURY	VENUS
Date	March 15	March 15
Magnitude	0.5	–4.4
Angular size	8.7"	21.3"
Illumination	36%	56%
Distance (AU) from Earth	0.773	0.785
Distance (AU) from Sun	0.446	0.718
Right ascension (2000.0)	22h04.3m	2h28.7m
Declination (2000.0)	–11°26'	17°04'

March 2020

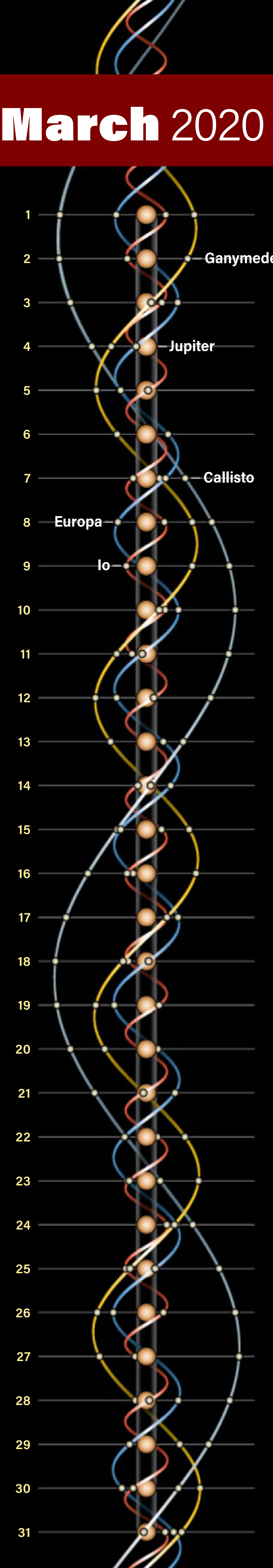
This map unfolds the entire night sky from sunset (at right) until sunrise (at left). Arrows and colored dots show motions and locations of solar system objects during the month.



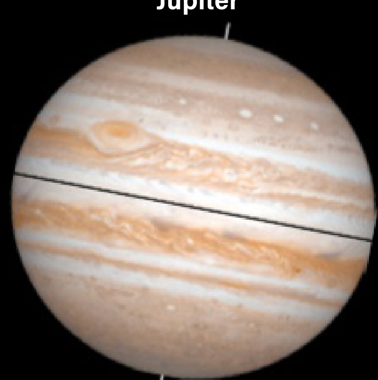
Early evening

JUPITER'S MOONS

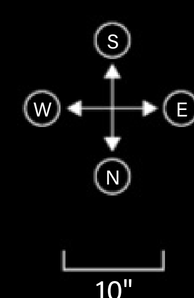
Dots display positions of Galilean satellites at 6 A.M. EDT on the date shown. South is at the top to match the view through a telescope.



Jupiter



Saturn



Uranus Neptune Pluto

MARS	CERES	JUPITER	SATURN	URANUS	NEPTUNE	PLUTO
March 15	March 15	March 15	March 15	March 15	March 15	March 15
1.0	9.3	–2.0	0.7	5.9	8.0	14.8
5.9"	0.4"	35.3"	15.7"	3.4"	2.2"	0.1"
90%	99%	99%	100%	100%	100%	100%
1.598	3.662	5.578	10.557	20.567	30.920	34.481
1.497	2.951	5.200	10.026	19.809	29.932	33.999
19h21.5m	21h23.2m	19h33.8m	20h05.2m	2h07.7m	23h18.8m	19h45.4m
–22°46'	–21°35'	–21°43'	–20°22'	12°26'	–5°32'	–22°01'

 — *Continued from page 37*

Luna enhances a planetary pageant

The Moon nearly overshadowed Jupiter (far right), Mars, and Saturn (far left) on March 8, 2018. March 18 sees the same quartet more tightly grouped. RYAN IMPERIO

daylight time every morning of March. It's worth planning to rise early and check them out. March mornings host two planetary conjunctions — one between Mars and Jupiter set against the backdrop of eastern Sagittarius on March 20, followed by a second between Mars and Saturn in western Capricornus on March 31.

There's a beautiful prelude to the first conjunction when the waning crescent Moon stands about 2° away from Jupiter and Mars, with the planetary duo residing just 1.3° apart in the predawn sky March 18. Search for Saturn 7° east of these two. By the morning of March 19, the Moon has passed to the east of Saturn and stands 7° east-southeast of the ringed planet.

The extraordinary planetary show continues on the morning of March 20, when Jupiter and Mars are in conjunction. The pair rises at about 4 A.M. and climbs 10° high in the southeast an hour later. At this point, Mars sits 42' south of Jupiter. Jupiter shines with a yellowish light at magnitude –2.1, while Mars' magnitude 0.9 orange glow provides a lovely contrast.

Target the duo with a telescope at low power, as both are visible in the same field of view. Mars' diminutive disk spans just 6", while Jupiter's disk measures an impressive 36". At a distance of 139 million miles, Mars sits 50 percent farther from the Sun than Earth, while Jupiter is much farther away at 511 million miles. Thanks to its small angular size, you'll be hard-pressed to make out many visible features on the martian surface. In contrast, Jupiter's cloud tops are bursting with detail. Furthermore, the solar system's largest planet is joined by at least three jovian moons. Io enters eclipse around 5:30 A.M. EDT on March 20 and will remain hidden after that. Jupiter's classic pair of dark equatorial belts are visible straddling the equator, and more subtle dark belts lie to their north and south. With luck, you may even glimpse Jupiter's Great Red Spot during this conjunction with Mars. Though the Red Planet and the Great Red Spot share a similar hue, their colors are due to different processes.

WHEN TO VIEW THE PLANETS

EVENING SKY
Venus (west)
Uranus (west)

MORNING SKY
Mercury (east)
Mars (southeast)
Jupiter (southeast)
Saturn (southeast)

The eastward motion of Mars carries it between Jupiter and Saturn through March 31, when the Red Planet stands 56' south of the ringed planet. Saturn and Mars shine with a similar magnitude: Saturn at magnitude 0.7 and Mars at magnitude 0.8. The brighter Jupiter stands 6° west of this majestic pair. Sadly, a telescope again reveals a nondescript surface on 6"-wide Mars,

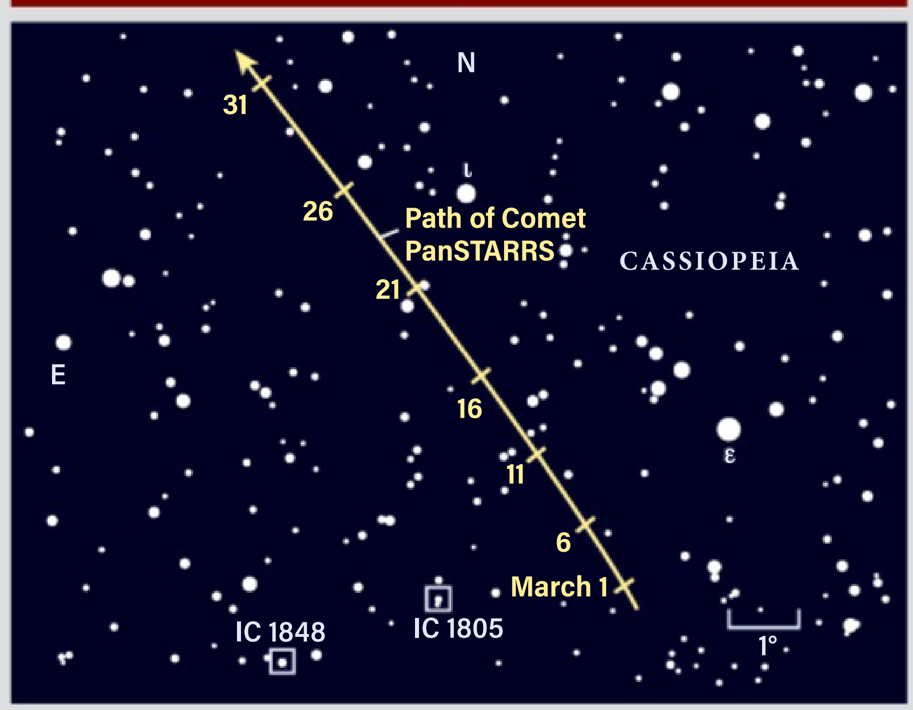
COMET SEARCH | Cruising through Cassiopeia

OBSERVERS AND IMAGERS REJOICE: The brightening Comet PanSTARRS (C/2017 T2) is getting better every week as it approaches its peak in early May. If you prefer to see it during the evening hours, you will have to wait until Friday the 13th, when the Moon's glare doesn't spoil the view until after midnight.

This is the last weekend that PanSTARRS is posing with the picturesque Heart and Soul nebulae in Cassiopeia. For electronic detectors, it will appear as a green fuzzball on a colorful background, but for organic eyeballs, the comet will look like a gray cotton ball on a misty backdrop. For suburban observers, the dirty snowball is likely a challenge to spot with even a 10-inch scope, but the 9th-magnitude nebulosity is quite noticeable when using a 4-inch scope under dark, country skies.

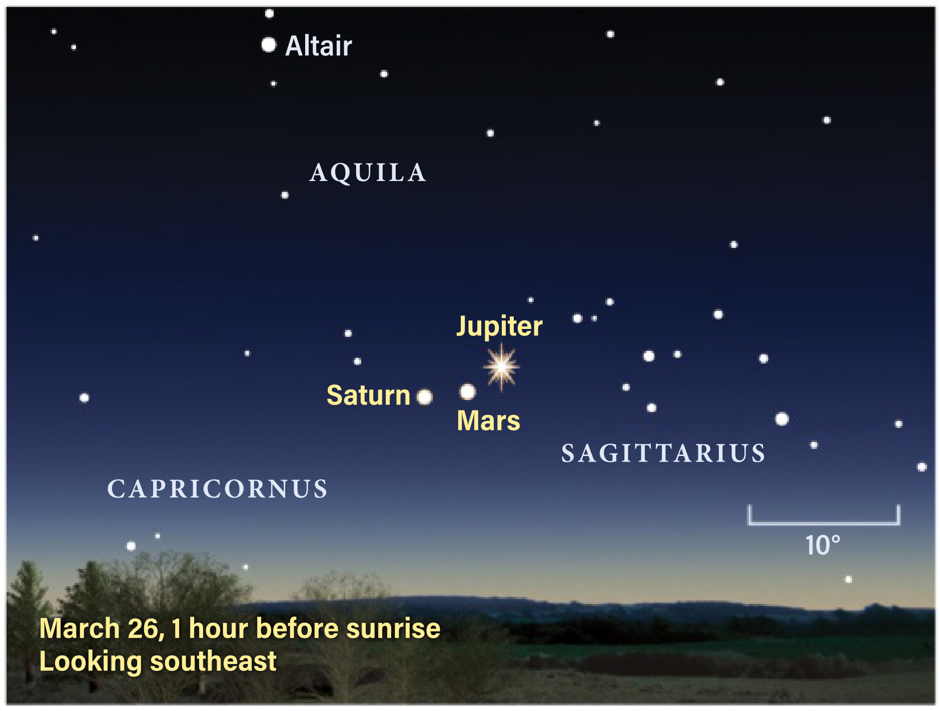
Well away from the city, an 8-inch aperture at a power of 200x will expose how the comet's characteristic shape differs from elliptical galaxies. Giving this a try with smaller instruments is also a great way to improve your skills. PanSTARRS' southern flank will be well-defined thanks to the solar wind and radiation pressure pushing on the comet's escaping gas and dust, creating a bow wave. The nucleus of the comet is invisible behind the shroud of dust, but this inner coma may shine like a star within the overall glow. On the northern side, the ball quickly spreads into the soft nothingness of empty space.

Comet PanSTARRS (C/2017 T2)



This first-time visitor to the inner solar system should glow near 9th magnitude as it heads northeastward against the backdrop of Cassiopeia.

Three planets triple the predawn pleasure



When Mars stands midway between Jupiter and Saturn on March 26, it highlights the closest meeting of these three worlds in 20 years.

but Saturn's dramatic rings span 37", while the planet itself stretches 16" across. At a distance of 957 million miles, Saturn stands twice as far from us as Jupiter. Under a dark sky at 5:30 A.M., the pair of planets stand 15° high.

Let's return to Jupiter for a moment, as the world is now high enough to witness some of the exciting activity of its Galilean moons. Ganymede's giant shadow falls on Jupiter's northern hemisphere March 10 at 6:53 A.M. EDT and is fully on the disk by 7 A.M.

Although Callisto missed the giant planet's disk during 2019, its transits are back in 2020. It begins a trek across the far northern latitudes of the jovian disk at 7:12 A.M. EDT March 14, when Midwestern observers can spot Jupiter riding 16° high. Earlier that morning, you can watch Io leave Jupiter's disk at 4:09 A.M. EDT followed by Ganymede reappearing on the planet's eastern limb at 4:51 A.M.

Finally, on March 31, Jupiter rises as Callisto is near the end of a transit, and the moon exits the jovian disk just after 6 A.M. EDT. In addition to Io's transit the morning of March 20, there will be a few more events involving the innermost Galilean moon this month and many more throughout the year.

By mid-March, **Mercury** makes an earnest leap into the morning sky following last month's inferior conjunction. Because of the low tilt of the ecliptic to the predawn eastern horizon, the pint-sized planet stays at a relatively low altitude throughout March. Rising an hour before the Sun on March 10, Mercury glows at magnitude 1. By 7 A.M. local daylight time, its climbed to 7° high, though the exact height differs depending on latitude.

Your best opportunity to spot the innermost planet is March 20 and 21, when a wafer-thin crescent Moon stands nearby. On both mornings, the Moon and Mercury rise an hour before the Sun. Thirty minutes later, Mercury climbs 5° high in the east-southeast. The Moon and the tiny planet sit 15° apart March 20, and just 5° apart the following day. Mercury glows at a modest magnitude 0.2.

Mercury reaches greatest western elongation March 23, at 28° west of the Sun, but the small planet doesn't gain any altitude. By March 31, you'll find it has brightened to magnitude 0.0, and stands 4° high 30 minutes before sunrise.

Martin Ratcliffe *provides planetarium development for Sky-Skan, Inc., from his home in Wichita, Kansas.* **Alister Ling**, *who lives in Edmonton, Alberta, has watched the skies since 1975.*

LOCATING ASTEROIDS

Tracking Vesta through Taurus

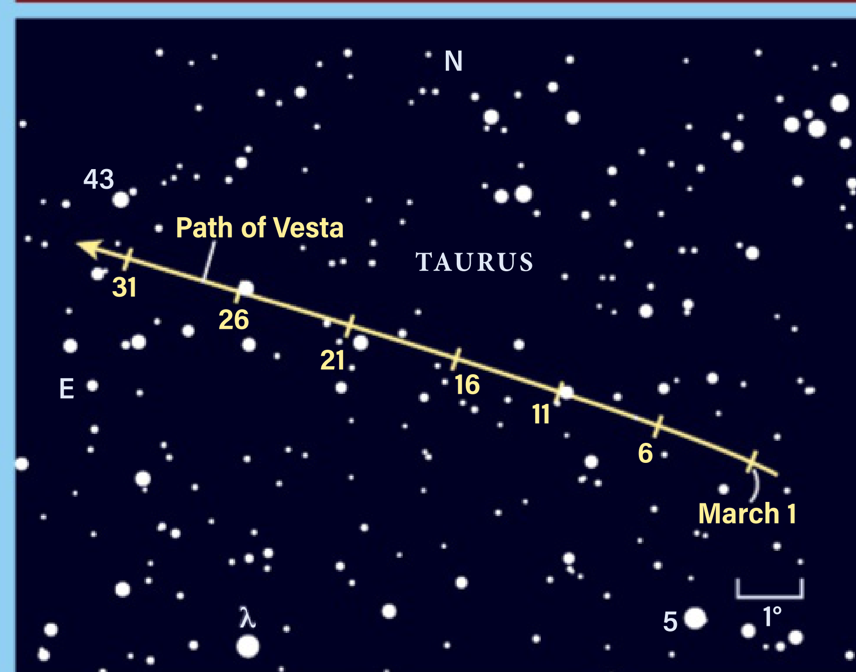
THE BRIGHT LUMINARY Aldebaran, the ruddy eye of the celestial Bull, guides us toward the field of Vesta in March. Beginning the night high in the west, as twilight deepens, the main belt asteroid slowly approaches the Hyades star cluster, which actually lies far in the background.

As the fourth asteroid to be discovered, Vesta was once thought to be part of an exploded planet. Our current understanding, bolstered by data from the orbiting Dawn spacecraft, is that it slowly grew as small planetesimals steadily globbed together. Unlike the darker space rocks out there, Vesta reflects 40 percent of the sunlight that hits it, helping it reach magnitude 8.5 and making it relatively easy to spot with a 4-inch scope from the suburbs.

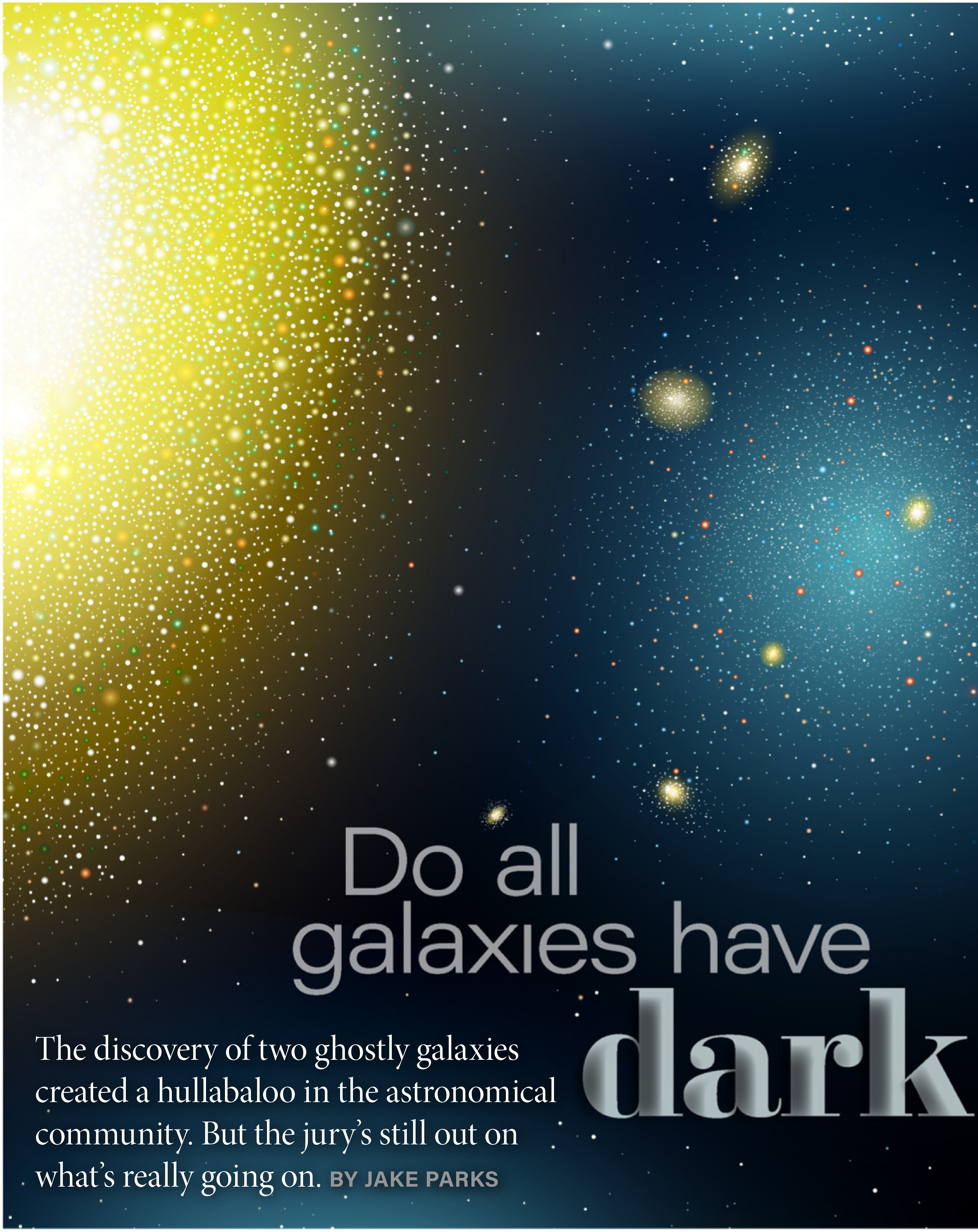
You might want to skip the first week's game of "asteroid or star?" when Vesta drifts across the nondescript background of the outer Milky Way. Instead, start about an hour after sunset, and note the asteroid's position. Then return about three hours later to notice its displacement. On March 11 and 26, Vesta separates from 6th-magnitude field stars. And it forms a line with two brighter background stars on the evening of March 19.

Observers with 8-inch scopes should make sure to check in on Vesta on March 7, when it pairs with a star only slightly brighter than itself. Much like Saturn doesn't twinkle to the eye, Vesta should have a slightly "flatter" character than stars, as long as our atmosphere is not too turbulent.

The Bull stares down Vesta

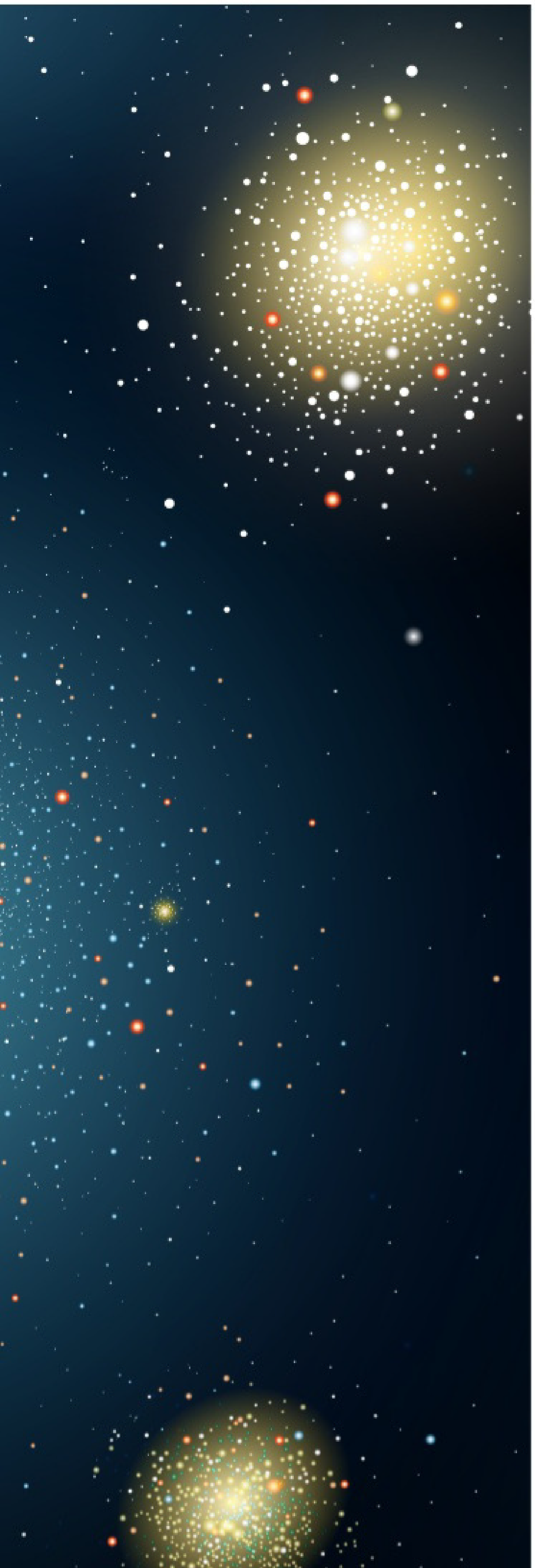


March evenings find this 8th-magnitude asteroid lurking among the myriad background stars of western Taurus.



Do all galaxies have dark

The discovery of two ghostly galaxies created a hullabaloo in the astronomical community. But the jury's still out on what's really going on. BY JAKE PARKS

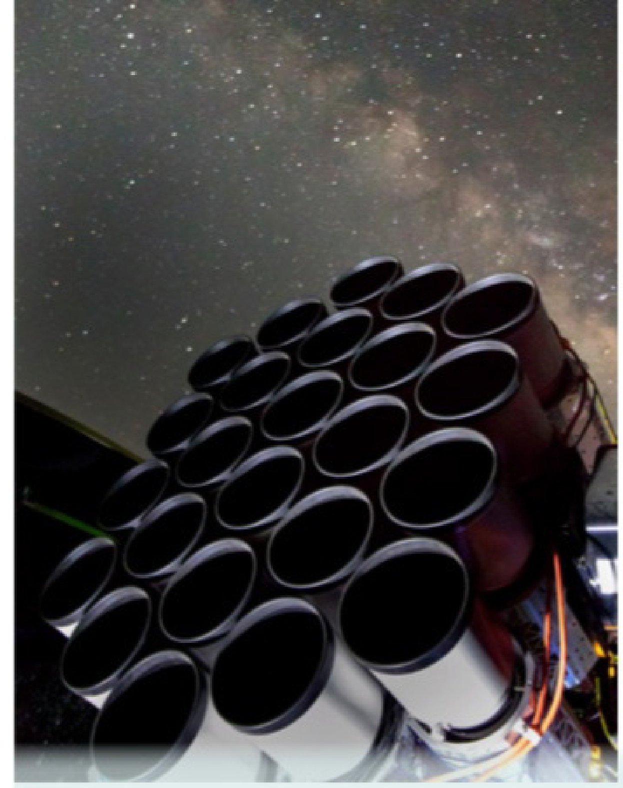


Some 60 million light-years from Earth — by some researchers' estimate, anyway — a pair of strange galaxies is causing a cosmic stir. These island universes hold far fewer stars than your average galaxy. But it's not the lack of stars that surprises astronomers. The bizarre galaxies, named NGC 1052-DF2 and NGC 1052-DF4 (or DF2 and DF4, for short), also seem to lack any significant amount of dark matter.

Because the duo could be the first known galaxies without the substance, which accounts for 85 percent of the universe's matter, news of DF2's discovery in 2018 quickly spread throughout the astronomical community. If confirmed, such galaxies without dark matter would throw a wrench into our understanding of how galaxies form and evolve.

"We thought that every galaxy had dark matter and that dark matter is how a galaxy begins," astrophysicist Pieter van Dokkum of Yale University, lead author of the initial paper on DF2, said in a press release. "This invisible, mysterious substance is the most dominant aspect of any galaxy. So finding a galaxy without it is unexpected. It challenges the standard ideas of how we think galaxies work, and it shows that dark matter is real: It has its own separate existence apart from other components of galaxies."

But as Carl Sagan liked to say, extraordinary claims require extraordinary evidence. And, according to some researchers, the evidence for these dark-matter-deficient galaxies doesn't hold up.



Stationed in New Mexico, the novel Dragonfly Telephoto Array has been built up over the years into a collection of 48 telephoto lenses bundled in two groups. Together, the 400mm lenses create the equivalent of a 1-meter refracting telescope and enable observations of extremely faint and diffuse cosmic structures. P. VAN DOKKUM (YALE)

What is DF2?

DF2, the first known galaxy supposedly devoid of dark matter, is a member of a unique class of galaxies called ultra-diffuse galaxies (UDGs). Although UDGs can grow as large as the Milky Way, these hazy specters contain hundreds to thousands of times fewer stars. And because they're essentially transparent, they're extremely difficult for astronomers to observe in detail.

The relatively innocuous DF2 first stood out to researchers when they identified it using the Dragonfly Telephoto Array. This robotic collection of Canon 400mm telephoto lenses combine to

Astronomers uncovered two see-through galaxies that appear to be devoid of dark matter. And because they lack the strange substance, their globular clusters move much more slowly than expected. *ASTRONOMY*: ROEN KELLY

create a novel telescope that's particularly adept at imaging expansive and extremely faint structures. When the researchers observed DF2 with Dragonfly, they noticed the galaxy looked different than it did in images taken with the Sloan Digital Sky Survey (SDSS). In the Dragonfly images, DF2 looked like a blob of dim and diffuse light, but in the SDSS images, it appeared as a group of pointlike sources.

To investigate this discrepancy, van Dokkum's team went on to observe DF2 using the Advanced Camera for Surveys on the Hubble Space Telescope, and performed follow-up spectroscopic observations with the Keck Telescope.

"I spent an hour just staring at the Hubble image," said van Dokkum. "It's so rare, particularly these days after so many years of Hubble, that you get an image of something and you say, 'I've never seen that before.' This thing is astonishing — a gigantic blob that you can look through. It's so sparse that you see all of the galaxies behind it. It is literally a see-through galaxy."

Using the Hubble data, van Dokkum and his team measured the galaxy's surface brightness fluctuations, which is a rudimentary distance indicator based on the fact that more distant galaxies appear more uniform in brightness. From this, the researchers calculated DF2 is located about 65 million light-years away.

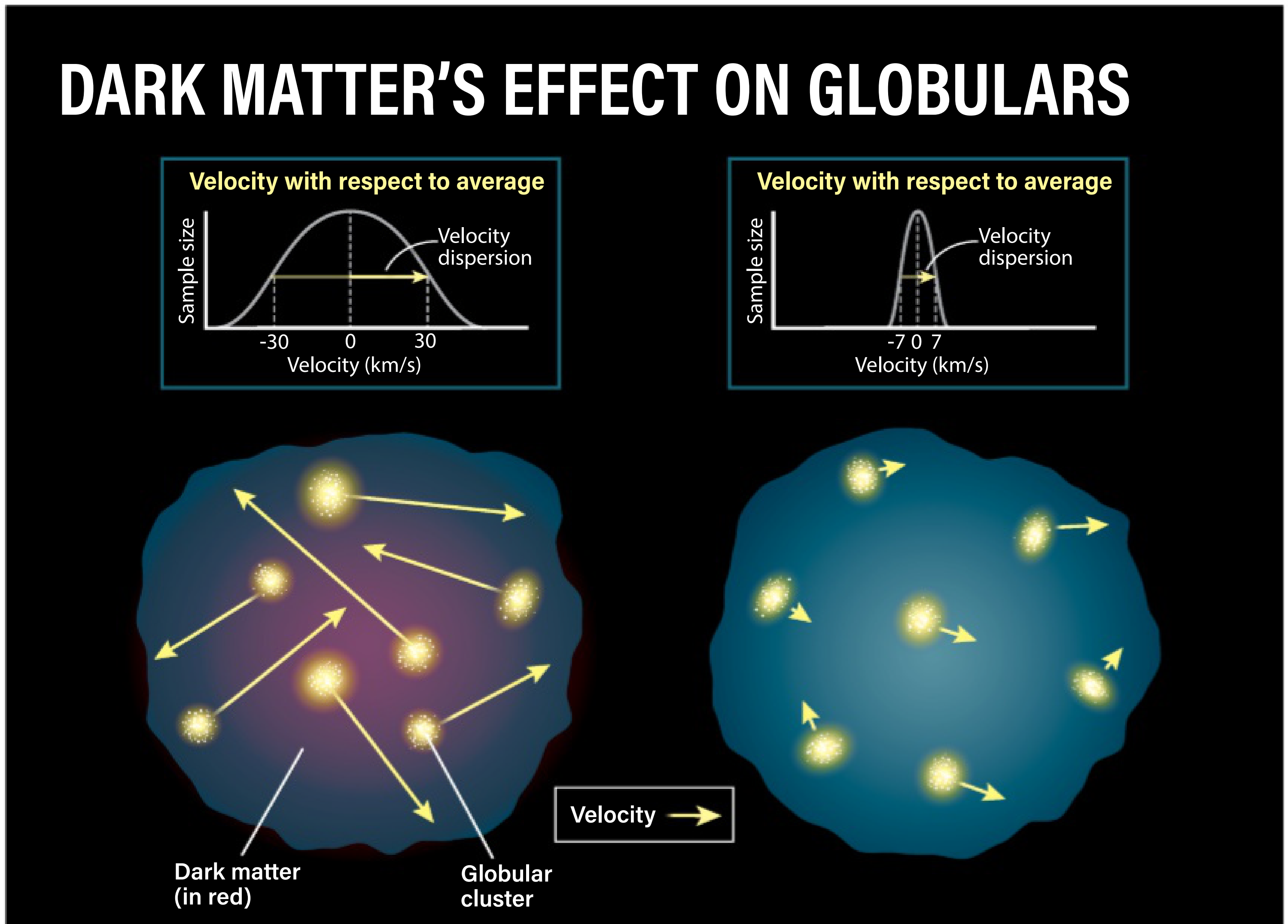
> **"I spent an hour just staring at the Hubble image."**
>
> Pieter van Dokkum

Then, based on the Keck data, van Dokkum's team identified globular clusters (large, spherical groups of old stars) within DF2. Surprisingly, they found the globular clusters were moving at a snail's pace compared to what we would see if the galaxy were chock-full of dark matter. If DF2 had more dark matter, van Dokkum says, the increased gravitational pull would cause these clusters to move about three times faster than they do.

The realization that DF2 seems to have very little, if any, dark matter caught the researchers off guard because it's the first galaxy found lacking the pervasive material. "There is no theory that predicted these types of galaxies. The galaxy is a complete mystery, as everything about it is strange," said van Dokkum. "How you actually go about forming one of these things is completely unknown."

However, not everyone agrees that DF2 is missing its dark matter.

Hubble captured this beautiful image of the transparent galaxy DF2 with its Advanced Camera for Surveys. NASA/ESA/P. VAN DOKKUM (YALE)



GALAXIES WITH DARK MATTER. In diffuse galaxies, globular star clusters typically do not orbit around their galaxies in circular paths like they do in spiral galaxies. Instead, they have a range of radial orbits that carry them every which way. If dark matter dominates a diffuse galaxy, the globulars within it should be moving relatively fast, as seen above. *ASTRONOMY*: ROEN KELLY

GALAXIES WITHOUT DARK MATTER. However, in diffuse galaxies without dark matter, the lack of hidden mass means that globular clusters within the galaxies move much more slowly. In the case of DF2 and DF4, researchers found that the globulars are moving so slowly that the mass of the galaxies' visible matter alone is enough to account for their motions. *ASTRONOMY*: ROEN KELLY

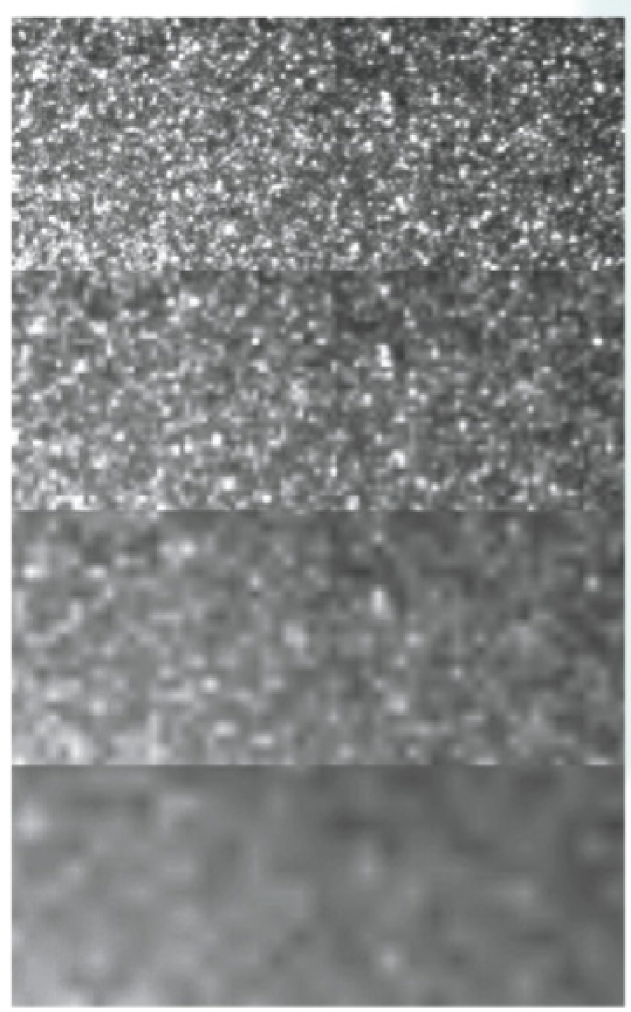
Debating DF2's distance

"Something that caught my attention very early on was the fact that the galaxy was not only anomalous for not having dark matter, but also for having an extraordinarily bright population of globular clusters," says Ignacio Trujillo of the Instituto de Astrofísica de Canarias, who led the main study challenging the bizarre nature of DF2. "I remember thinking: 'Two anomalies at the same time really looks odd.'" This led Trujillo to consider whether DF2 is really as distant as van Dokkum's team thinks.

If DF2 were roughly 65 million light-years away, like van Dokkum suspects, then it would be a strong candidate for the first example of a galaxy without dark matter. But Trujillo says that if DF2 is closer, the galaxy's observed properties would fall in line, more or less, with what's expected from your typical dark-matter-dominated galaxy.

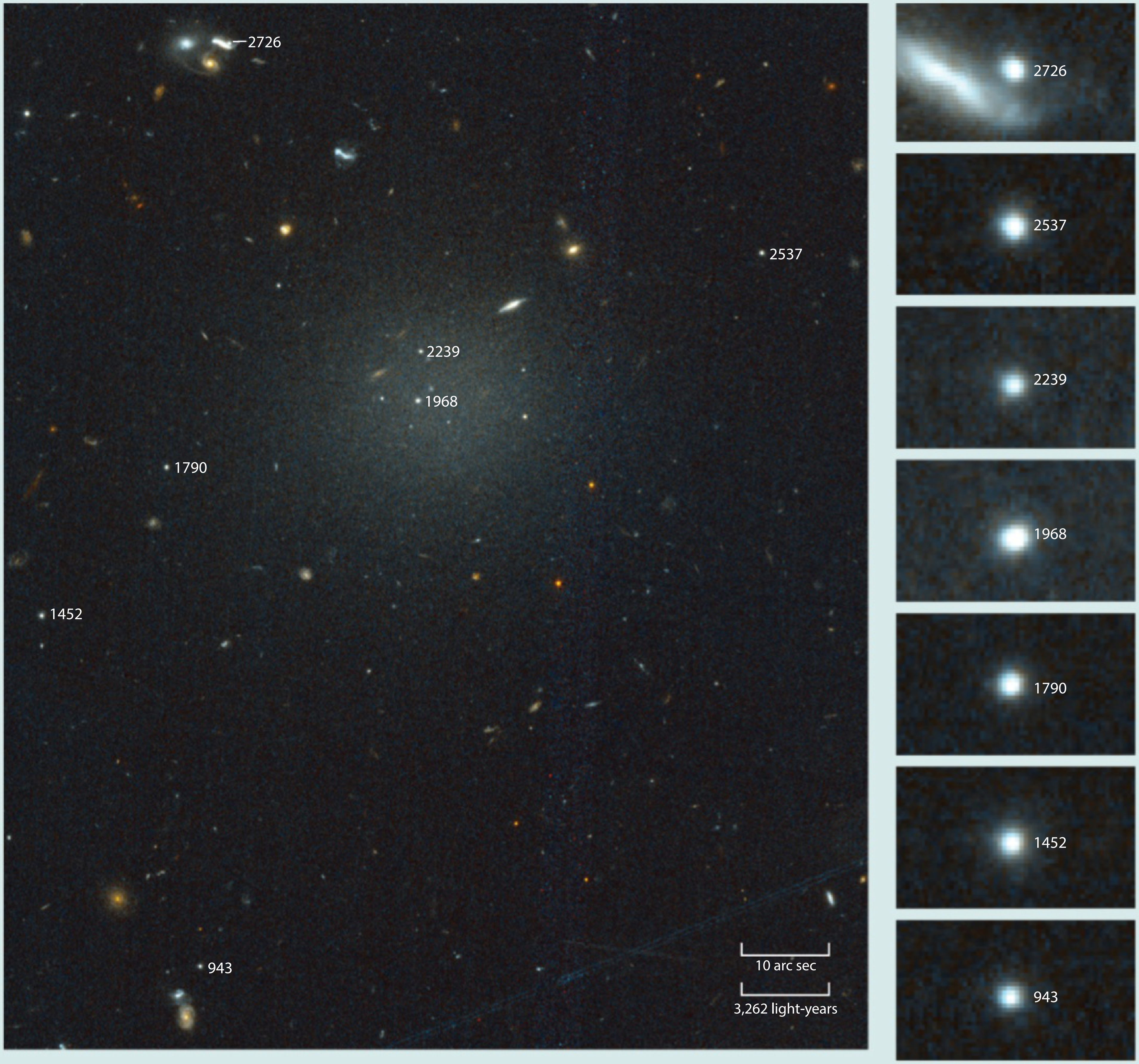
To test their theory, Trujillo and his team set off to independently determine the distance to DF2 using five different methods — all with varying degrees of trustworthiness.

Two of the methods relied on analyzing the brightnesses and sizes of DF2's globular clusters. According to the short-distance camp, if DF2 is closer than initially thought, then the galaxy's globular clusters no longer would be weirdly big and bright. Trujillo's team also compared DF2's properties to a

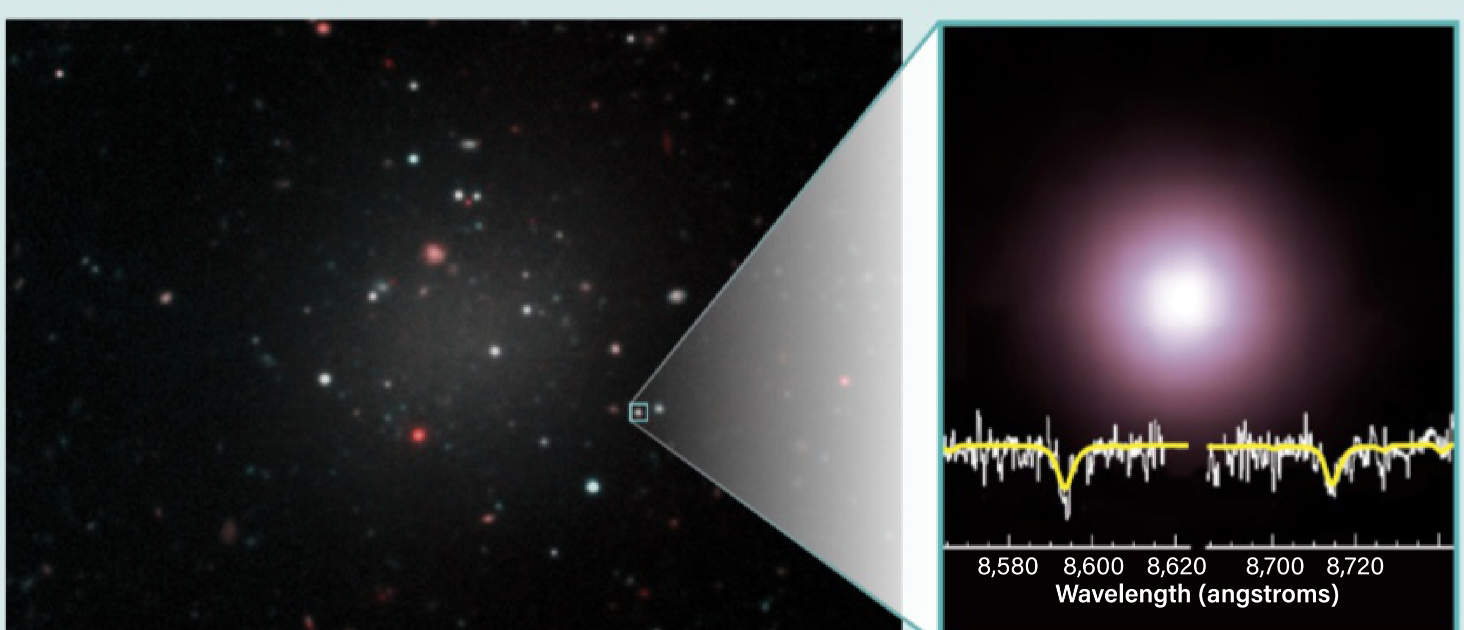


The basic idea of the surface brightness fluctuation method for determining distance is that the farther away a galaxy is, the smoother its overall brightness profile. This is because each pixel of an image contains a lot more stars for more distant galaxies. This image uses resampled Hubble data to show what M32 would look like at increasingly greater distances (nearest is at top, farthest is at bottom). NASA/ESA/W. KEEL (UNIVERSITY OF ALABAMA)

CLOCKING GLOBULAR CLUSTERS



ABOVE: Shortly after determining galaxy DF2 is lacking dark matter, van Dokkum and his team identified another galaxy, DF4, that likewise seems to be missing the mysterious substance. The highlighted objects are DF4's globular clusters. VAN DOKKUM ET AL. (2019)



LEFT: To determine how quickly the globular clusters were moving in DF2, the researchers analyzed the absorption lines found in each globular cluster's spectrum. This revealed clues about the clusters' motions, and researchers then used this information to calculate the overall mass of the galaxy. GEMINI OBSERVATORY/NSF/AURA/W.M. KECK OBSERVATORY/JEN MILLER/JOY POLLARD

similar galaxy, called DD044, which has a more reliable distance estimate, as well as recalculated DF2's distance using the same surface brightness fluctuation method (with different calibrations) as van Dokkum's team.

Finally, Trujillo's team analyzed the tip of the red giant branch (TRGB) in DF2's color-magnitude diagram, which plots the surface temperatures and luminosities of stars within a galaxy. Because the brightest red giant stars all shine with same true brightness in infrared light, the only thing that should dramatically impact how bright they appear to us is their distance. So, by identifying how bright the stars on the TRGB look for a given galaxy, researchers can get a good grasp on how far away the galaxy really is.

"This is, by far, the most accurate way of measuring the distance to the galaxy if the data have good quality," Trujillo says. Based on all five methods, Trujillo and his team determined DF2 is likely only about 42 million light-years away, rather than some 65 million light-years away. This, Trujillo argues, would mean that DF2 isn't as strange as initially thought, and instead harbors about as much dark matter as you would expect from an average, run-of-the-mill galaxy.

> "There is no theory that predicted these types of galaxies. The galaxy is a complete mystery, as everything about it is strange."
>
> **Pieter van Dokkum**

But van Dokkum isn't convinced by this competing distance determination.

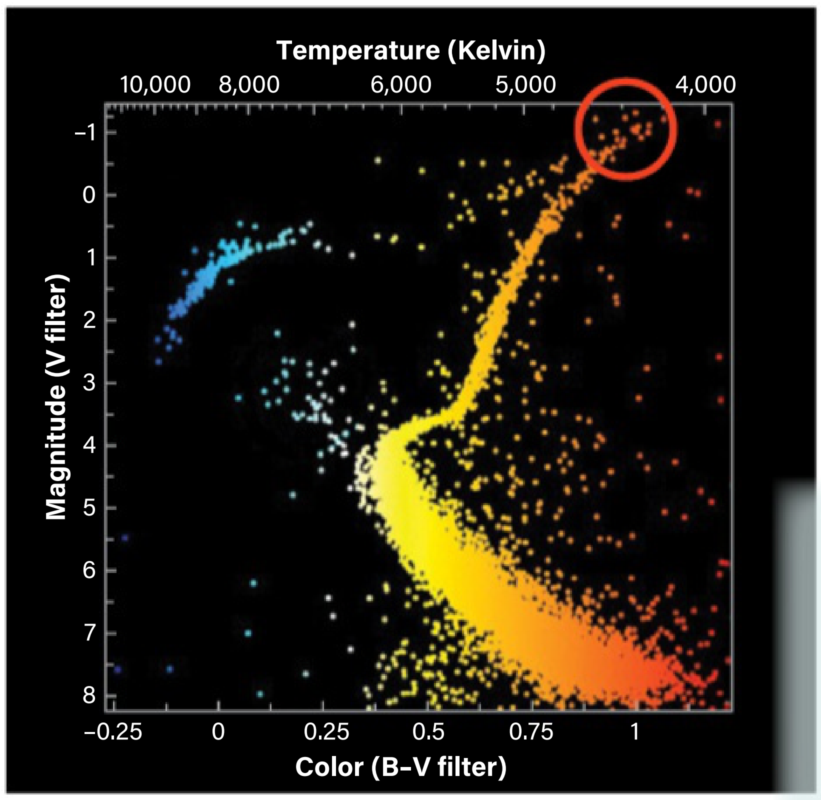
In August 2018, his team published yet another paper in response. In it, they argue Trujillo's "five 'independent measurements' are a bit misleading." For instance, van Dokkum says, "three of them are circular, in the sense that the authors argue that the properties of the galaxy would be less strange if it were at a closer distance." Plus, van Dokkum argues, the short-distance camp based their most convincing distance estimate on a "phantom" TRGB that's nearly twice as bright as the galaxy's true TRGB. This, van Dokkum says, led Trujillo's team to calculate a distance to DF2 that's only about 70 percent the actual value.

After showing why they think Trujillo's shorter distance to DF2 was due to blends in the TRGB data — where multiple stars were counted together as a single, bright red giant — van Dokkum's team went on to provide a new distance measurement to DF2 they claim is independent of calibration uncertainties. Their result: DF2 is about 61 million light-years away, which would mean DF2 still has a negligible amount of dark matter.

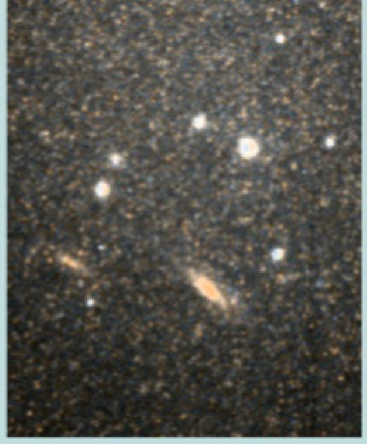
What about DF4?

But the debate didn't stop there.

After this academic back-and-forth, van Dokkum and his team found a second galaxy, DF4, which is nearly a clone of DF2 in terms of its size, surface brightness, morphology,



Stars at the tip of the red giant branch (circled in red) all shine with nearly the same intrinsic brightness when viewed in a certain band of light, despite differences in their composition or mass. So, if you measure how bright these stars appear, you can get a good estimate of their distance. *ASTRONOMY:* ROEN KELLY



NASA/ESA/P. VAN DOKKUM (YALE)

HOW DID THESE GALAXIES FORM?

Although there is no generally accepted way to form a galaxy without dark matter, according to van Dokkum's initial paper on DF2, the team does have a few ideas about how it could have happened.

One possible scenario is that DF2 is actually a tidal dwarf galaxy. This type of galaxy can form during galactic mergers, which often fling out baryonic material — ordinary matter made of neutrons, protons, and electrons, such as stars and gas. However, DF2's composition isn't quite right: It appears to have fewer metals, or elements heavier than helium, than would be expected for a tidal dwarf galaxy.

Another option is that DF2 formed when winds from a nearby quasar swept together large clouds of low-metallicity gas, but the researchers point out that the see-through galaxy may be too diffuse for this to be a likely scenario.

Finally, the researchers suggest DF2 could have formed when clouds of gas — located in the space between nearby galaxies and flowing toward the suspected gravitational anchor of the galaxy group, NGC 1052 — broke away from the stream. Shocks in the gas, caused by jets from NGC 1052's central supermassive black hole, could have disrupted some of the flow, forming DF2. However, all of these are just hypotheses, and the researchers are working first to prove galaxies without dark matter really exist before diving into their origin stories.

location, and distance. But, most importantly, DF4 likewise has an apparent dearth of dark matter.

Using the Keck Telescope to measure the motion and speed of DF4's diffuse gas, as well as seven of its globular clusters, van Dokkum's team calculated that DF4's distance is similar to DF2's — hovering around 65 million light-years away, give or take about 9 million light-years.

"We conclude that NGC 1052-DF2 is not an isolated case, but that a class of such objects exists," van Dokkum's team wrote in their DF4 discovery paper. "The origin of these large, faint galaxies with an excess of luminous globular clusters and an apparent lack of dark matter is, at present, not understood."

But, yet again, Trujillo and his team calculated their own distance to DF4. Based on Hubble data available at the time, they identified what they think is DF4's TRGB. This led them to conclude that DF4 is about 46 million light-years away, which would mean its globular clusters aren't actually that strange, and instead are pretty similar to those found in the Milky Way and elsewhere.

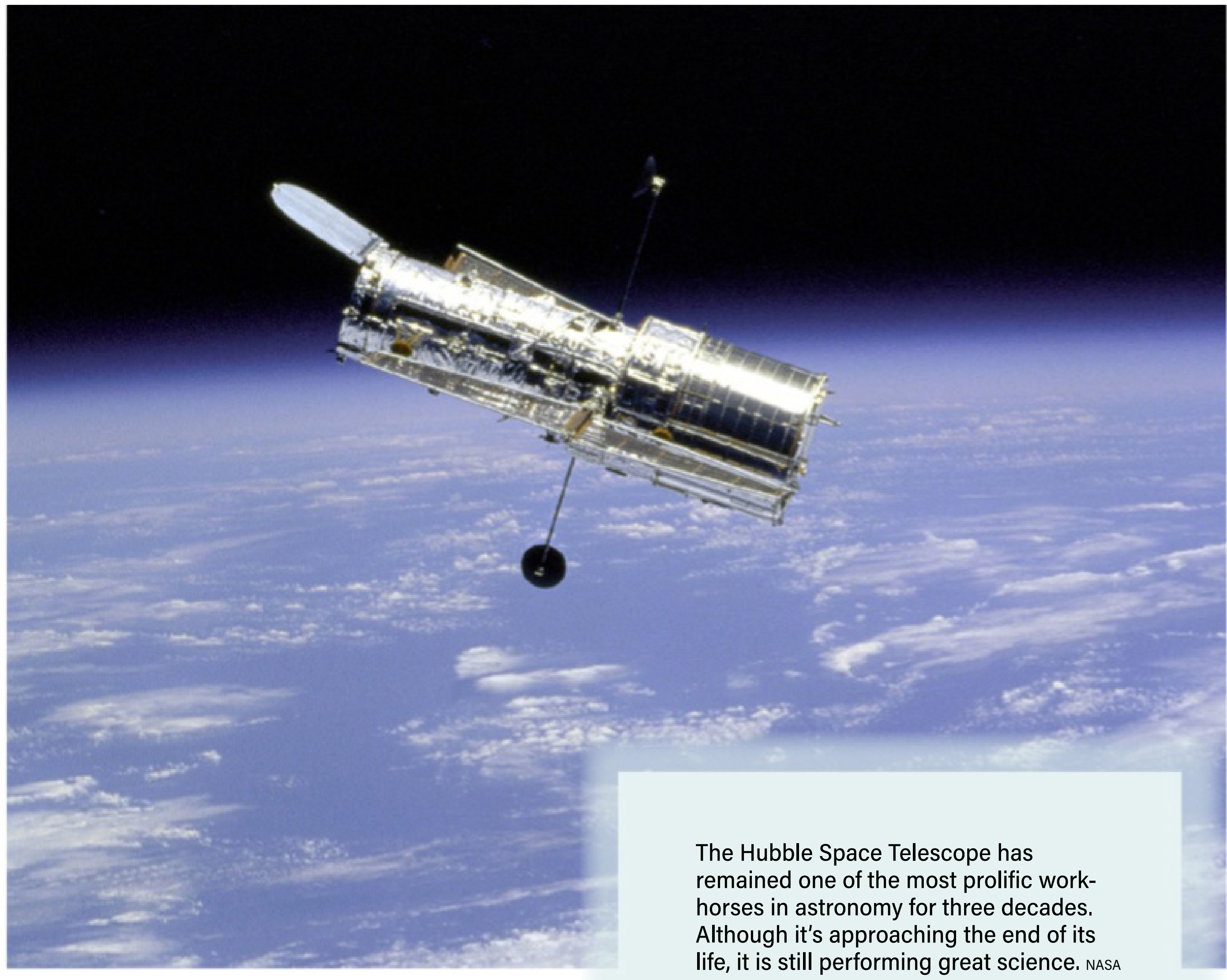
"All in all," Trujillo's team concluded in their response paper, "the proposition that both NGC 1052-DF2 and NGC 1052-DF4 are 'missing dark matter' is still far from being placed on sure footing."

Hubble takes another look

In the summer of 2019, in order to determine whether Trujillo's team had identified DF4's true TRGB, van Dokkum's group used Hubble's keen eye to collect new, deep images of DF4. On October 16, they posted another paper, which has been submitted to *The Astrophysical Journal Letters,* on the preprint site arXiv. Based on the fresh Hubble data, which picked up many more, much fainter stars, the paper claims the short-distance camp again misidentified DF4's brightest red giant stars, leading to a closer derived distance.

"In the new data, there really is no ambiguity," says study author Shany Danieli of Yale, who is van Dokkum's colleague. "We think the new data really rule out the [shorter-distance] option."

"I think this is definitive," says van Dokkum. "The TRGB cannot be argued with: It is caused by well-understood stellar physics, and [is] as direct as distance indicators get."



The Hubble Space Telescope has remained one of the most prolific workhorses in astronomy for three decades. Although it's approaching the end of its life, it is still performing great science. NASA

> **"At the moment, I remain enormously skeptical about their outcome of a long distance for DF4."**
>
> Ignacio Trujillo

But after reviewing the new research, Trujillo is still dubious of the study's conclusion. "At the moment, I remain enormously skeptical about their outcome of a long distance for DF4," Trujillo says. "The first thing you should note is that this paper has still not [been] accepted by the referee and/or the journal," he explains. "It has been only submitted; therefore, further changes of its content can be expected after a careful reading by the referee."

Then there's also the matter of how van Dokkum's long-distance camp selected which of DF4's stars they would include in their TRGB analysis, which is yet another point of contention. "I think there are a number of choices [van Dokkum's group] have used that have not been justified," Trujillo says. "All of these choices seem to be selected to favor a larger distance than what the data suggests."

One such choice, Trujillo explains, is that the quality cuts van Dokkum's team used to pick which stars were included in their analysis seem to ignore many stars. Another, he adds, is that van Dokkum's team made "a preselection of their stars based on the colors" and they do not explain why or how that impacts their outcome. Both of these choices, Trujillo says, could greatly impact the derived distance to DF4.

What's next?

So, at this stage, the answer to whether DF2 and DF4 have dark matter or not is still largely up in the air.

ABOVE: After imaging DF2 and DF4 with the Dragonfly Telephoto Array, scientists used Keck Telescope in Hawaii to spectroscopically measure the velocity of the galaxies' globular clusters, revealing they lack dark matter. NASA/JPL

LEFT: The Bullet Cluster exemplifies how dark matter is a separable substance. As two giant galaxy clusters collided, normal matter (pink) was trapped between non-interacting clouds of dark matter (blue). NASA/CXC/M. WEISS

But just before this issue went to press, new research published November 25 in *Nature Astronomy* reported the discovery of 19 dwarf galaxies that likewise seem to be severely lacking in dark matter. So stay tuned for more on that in a later issue.

However, no matter what's really going with these galaxies without dark matter, van Dokkum says, "The broader point is that these are fascinating galaxies, and all aspects of our findings should certainly be questioned and scrutinized."

So if these latest results hold up to the scrutiny that's likely to come, then finding galaxies missing dark matter would completely change our understanding of how we think galaxies form and evolve.

"The galaxies point to an alternative channel for building galaxies — and they even raise the question whether we understand what a galaxy is," says van Dokkum. Right now, we think that galaxies begin with dark matter, which is how they're able to gravitationally attract the massive amounts of gas and dust needed to kick-start star formation.

"The thing is, we have no idea how star formation would proceed in the absence of dark matter," van Dokkum says. "All we can say is that there must have been very dense gas early on in their history," otherwise, galaxies without dark matter couldn't create new stars.

But is this latest distance determination to DF4 really robust enough to start exploring the implications of finding a galaxy without dark matter?

"Yes, that's our hope. We'd love to move to discuss what these galaxies mean, rather than whether our measurements were correct," Danieli says.

"That said," she adds, "we fully agree with everyone that 'extraordinary claims require extraordinary evidence.'"

Associate Editor ***Jake Parks*** *has long been fascinated by dark matter, and looks forward to learning more about the mysterious substance in the years and decades to come.*

Secrets of the Northern Pinwheel Galaxy

Think you know the big spiral M101?
Take a deep dive into its myriad details,
and you'll know it like never before.

STORY AND IMAGES BY ROD POMMIER

The image on the left is a close-up of M101's western spiral arm taken shortly after the discovery of Supernova 2011fe. The supernova appears as a bright blue star (indicated by tick marks). In the image at right, taken last year, the supernova has faded into obscurity. SN2011fe was a type Ia supernova, and you can see that it is not associated with any of M101's numerous HII regions. Because type Ia supernovae are all equal in luminosity, they serve as standard candles for estimating cosmic distances; this one helped pin down the distance to M101.

WHEN YOU HEAR "THE PINWHEEL GALAXY," YOU probably think of M33 in Triangulum. However, there's another galaxy that carries the same nickname: **M101** (NGC 5457) in Ursa Major. To distinguish it from M33, some refer to M101 as the Northern Pinwheel Galaxy. Upcoming spring nights will bring M101 into prime viewing position for deep-sky observers in the Northern Hemisphere.

As you might imagine, two galaxies with the same nickname have many similarities. Both are Hubble Type Sc galaxies with small central hubs and open spiral arms. Both present us with nearly face-on views. And both appear quite large in the sky. M33 has an apparent size of 67' by 42', so it covers 3.7 times the area of the Full Moon. M101 has a smaller apparent size of 30' by 27' — but that's still as big as the Full Moon! For deep-sky observers, the most unfortunate similarity is that both galaxies appear quite dim in the eyepiece. While M33 is listed at magnitude 5.7 and M101 is not far behind at magnitude 7.8, spreading the galaxies' light over their respective large surface areas renders them dim indeed. In fact, it's easy for first-time observers to pass right over these galaxies without seeing them because they are so much larger and dimmer than expected.

Perhaps the most exciting similarity between the Pinwheels is that they both offer rare opportunities to observe deep-sky objects within another galaxy. We naturally think of any galaxy as a single deep-sky object, but not so with the Pinwheels. As I wrote in the November 2014 issue of *Astronomy*, M33 contains four nebulae bright enough to have their own NGC numbers. And M101 contains 11 nebulae bright enough to have their own NGC numbers — more than any other galaxy.

The most likely reason for M101's record number of NGC objects is that astronomers believe M101 has undergone tidal interactions with dwarf galaxies in its group. The dwarf galaxy **NGC 5477** is the leading suspect. Computer simulations of a close interaction between such a dwarf and a classic spiral galaxy generate a good approximation of M101's appearance with a decidedly off-center core and far-flung spiral arms.

These tidal interactions triggered a collapse of numerous molecular clouds within M101 into active star-forming regions that have produced massive, hot, blue O and B stars. Those blue giants emit intense ultraviolet radiation that ionizes the hydrogen gas within their parent clouds, transforming them into bright reddish emission nebulae known as HII regions. The exciting news is that many of these nebulae are large and bright enough to be visible through backyard telescopes.

The NGC objects within M101 aren't easy prey, though. Observing them requires adequate aperture, dark skies, patience, and detailed maps. But finding them is well worth the effort. Locating faint NGC objects in our own Milky Way Galaxy is rewarding, but spotting them in a galaxy 21 million light-years away is a fantastic experience.

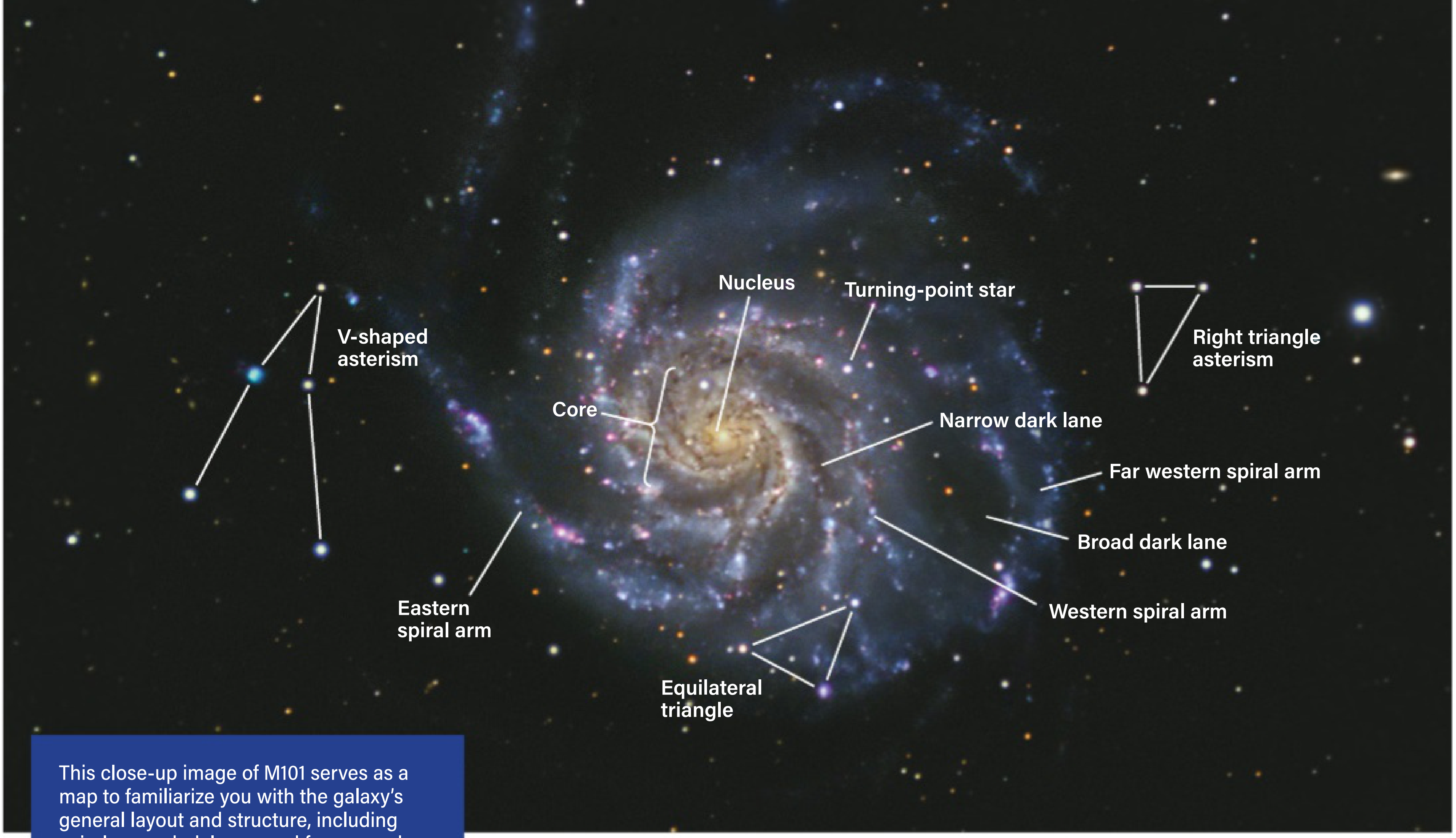
Being prepared will increase your chances of success. Before going out, study maps and images to acquaint yourself with foreground stars and M101's structures, including its spiral arms, and the relative positions of the NGC objects within them. After you have set up your telescope under dark skies, allow plenty of time for your eyes to fully dark adapt and protect your night vision by using a dim red flashlight to refer to the maps. Bring a variety of eyepieces.

Start with a low-power, wide-field ocular to familiarize yourself with the general layout of the Northern Pinwheel. If you identify the specific location of a target object but don't see it, try zooming in with a higher-power eyepiece. High-power eyepieces will darken the background and increase contrast, which can be essential for separating one of these NGC objects from the diffuse glow of their surrounding spiral arms. Using averted vision (glancing a bit off to the side of the area upon which you are concentrating) also may help you to spot some of the objects. However, I have not found that nebula filters noticeably help.

The big picture

Through a low-power, wide-field eyepiece, M101 presents itself as a large, faintly glowing circular area with a slightly brighter round core punctuated at its center by a small, nonstellar nucleus. Persistent scrutiny will reveal multiple spiral arms curving outward from the central core. I'll refer to the three arms in which we will hunt for nebulae as eastern, western, and far western, based on where they lie relative to

M101, the Northern Pinwheel Galaxy in Ursa Major, is thought to have undergone tidal interaction with the dwarf galaxy NGC 5477, which lies off the right edge of this image. This triggered formation of multiple bright star-forming emission nebulae known as HII regions, which you can observe through your telescope.



This close-up image of M101 serves as a map to familiarize you with the galaxy's general layout and structure, including spiral arms, dark lanes, and foreground Milky Way stars. Knowledge of these features will help you locate and identify faint NGC objects within the Northern Pinwheel. North is up and east is left.

the core. Be aware that even experienced deep-sky observers can find it challenging to decipher the patterns of M101's faint spiral arms.

The eastern spiral arm begins on the southwest side of the core and heads due south. It then hooks around the core, tapering into a long projection pointing northeast and ending in a narrow tip east of the core. The far western arm begins on the east side of the core and heads directly north. It becomes fainter as it angles sharply to the northwest, and remains barely visible (or vanishes in smaller scopes) as it broadly curves southwest. It brightens again as it passes on the east side of a group of three foreground stars that form a right triangle. The arm terminates southwest of the core by tapering into a bright, southward-pointing spearhead shape.

The western arm begins near a foreground star on the north side of the core and heads west toward another foreground star (turning-point star) where it abruptly turns south and then fans out. A broad dark lane separates it from the terminal portion of the far western arm and a narrow dark lane separates it from the eastern arm.

That nebula is enormous!

We'll begin with M101's easiest nebula, which actually lies well outside the visible galaxy. To the east of M101, just past the tip of the eastern arm, is a V-shaped asterism of five "stars," with the vertex pointing north. Careful scrutiny will reveal that the middle star on the east side of the V isn't a star at all (though I've seen more than one sketch of M101 where it is depicted as if it is). Rather, it's a circular fuzzy spot with a bright center. You've found the giant nebula **NGC 5471**.

NGC 5471 is a massive HII region actively forming hot, blue stars, which explains why a good portion of it appears intensely blue in images. Hubble images and stellar photometry indicate that it is approximately 200 times the size of the Orion Nebula and has been forming massive stars for at least 100 million years. Such stars live fast and die young within a few million years as type II supernovae. Observations by the orbiting Chandra X-ray Observatory show three bright X-ray sources within NGC 5471 consistent with supernova remnants. NGC 5471 can be spotted with a 6-inch scope.

Your patience and determination will be rewarded with the thrill of finding nebulae within a distant galaxy.

Nebulae in the eastern spiral arm

Scan westward from NGC 5471 to the tapered tip of the eastern spiral arm. Near the tip, you'll find an elongated, brighter region oriented from northeast to southwest. This is **NGC 5462**, which William Herschel first noted. Astroimages show many hot, blue giant stars mixed among hydrogen-alpha nebulosity. In September 1951, the type II supernova SN1951H appeared near the optical center of NGC 5462. The supernova reached magnitude 17.5. NGC 5462 is visible through an 8-inch scope.

Traveling farther inward along the eastern spiral arm, you'll come to another bright region located southeast of the core. This is the HII region **NGC 5461**. It resembles a faint, fuzzy star, like a dimmer version of NGC 5471. It also can be spotted with an 8-inch scope. If you have at least a 10-inch scope, then continue tracing the eastern spiral arm inward to where it joins the core. There you may find a small, dimly glowing patch of light, which is **NGC 5458**. Images show this nebula contains many blue giant stars.

This image of M101 details the locations of the NGC objects within the Northern Pinwheel Galaxy. Use of this map in conjunction with the one on page 54 will help you determine the relative positions of the fainter NGC objects when observing through your telescope.

The western spiral arm

If you have at least a 12-inch scope, trace the western arm outward from where it abruptly turns south; about 3.3' southwest of the galaxy's nucleus, you'll find a small bright area hugging the edge of the narrow dark lane. This is **NGC 5453**. Continue to follow the western arm south and you'll find a triangle of "stars" framing the area where it fans out and vanishes. Again, I've seen more than one sketch depicting all three points of this triangle as foreground stars, but the southernmost point is not a star — careful examination shows it has soft edges. This is the nebula **NGC 5455**. This HII region is where the type II supernova 1970G appeared in July 1970, reaching magnitude 11.5. The remnant of this supernova has since been observed by Chandra as a bright, compact X-ray source. Brighter than NGC 5453, NGC 5455 can be seen with an 8-inch scope.

Type II supernovae — explosions of single, massive stars — are strongly associated with HII regions of galaxies, where such stars are born. By contrast, type Ia supernovae, which occur when a white dwarf in a binary system gravitationally siphons enough gas off its companion to explode, are not necessarily associated with HII regions. On August 24, 2011, the type Ia supernova 2011fe (originally designated PTF11kly because it was detected by the Palomar Transient Factory) appeared within this spiral arm of M101 and was visible in amateur scopes. You can see SN2011fe as a bright blue star within the western spiral arm in the image of M101 I took after it was discovered (page 53). But in a matching close-up from the images taken last year for this article, SN2011fe had vanished into obscurity.

This type Ia supernova appeared in a faint portion of this spiral arm, rather than within one of M101's numerous HII regions. Type Ia supernovae explode when a white dwarf reaches 1.4 solar masses, and thus are equal in brightness. Therefore, they serve as standard candles for calculating cosmic distances; SN2011fe helped refine our estimate of the distance to M101.

Nebulae in the far western spiral arm

A few more treasures hide in the far western arm. Trace the arm outward from the core until you reach the bright, southward-pointing spearhead shape at the tip. A magnitude 14 foreground star marks its northwest edge. This bright shape is produced by the combined light of two adjacent nebulae: **NGC 5450** in the southern half and **NGC 5447** in the northern. Larger apertures may allow you to see the narrow dark gap between them.

If you have a large scope, you can try to spot M101's two most difficult targets. Check the far western arm at a point just south of a line between the southern star in the right triangle and the galaxy's nucleus. If you see a subtle brightening there, you've found **NGC 5449**. Next, check the point two-thirds of the way along a line between the southern star in the right triangle and the turning-point star where the western arm abruptly turns south. A tiny bright spot there might be **NGC 5451**. However, be advised that a faint close double star in the Milky Way may fool you into thinking you've seen NGC 5451 when you haven't.

The thrill of the challenge

I hope you will enjoy the thrill of hunting for these challenging NGC objects within M101. Your patience will be rewarded with the still-greater thrill of finding nebulae within a distant galaxy. Then, the next time someone mentions "The Pinwheel Galaxy," you can both impress and surprise them by saying "Oh, yes, the Pinwheel, in Ursa Major!"

Rod Pommier *is a surgeon and longtime deep-sky observer who has written many articles for* Astronomy.

Use this map to aim your telescope in the general area of the features shown.

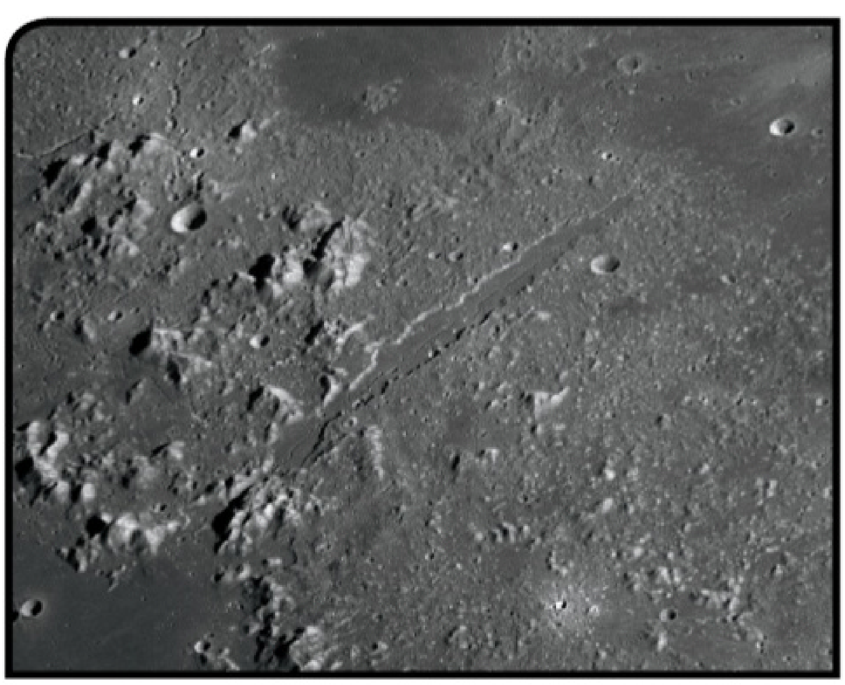
NASA'S SCIENTIFIC VISUALIZATION STUDIO

Explore the MOON AT FIRST QUARTER

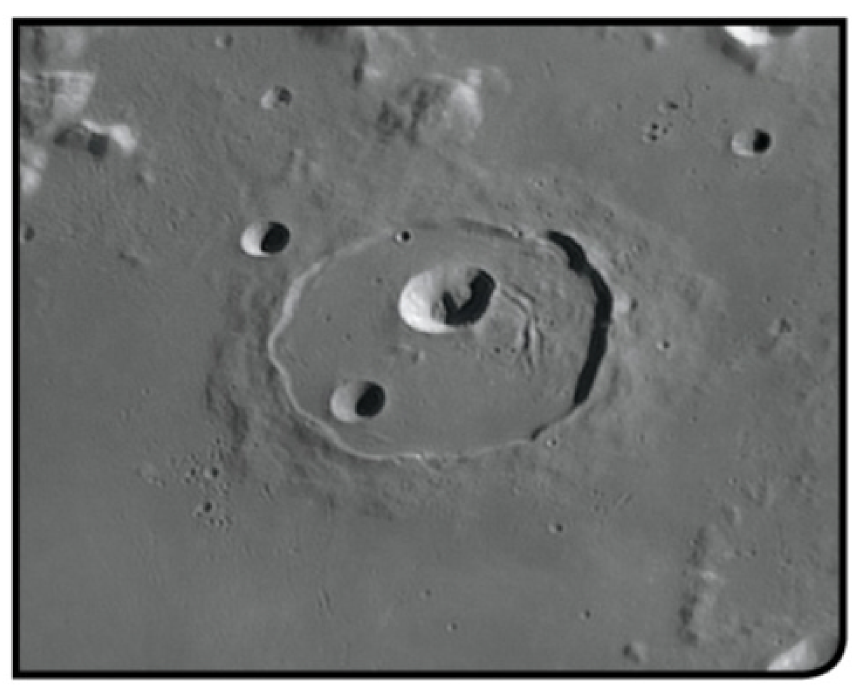
If you're just starting out, our natural satellite makes a tempting target in the evening sky.

BY MICHAEL E. BAKICH

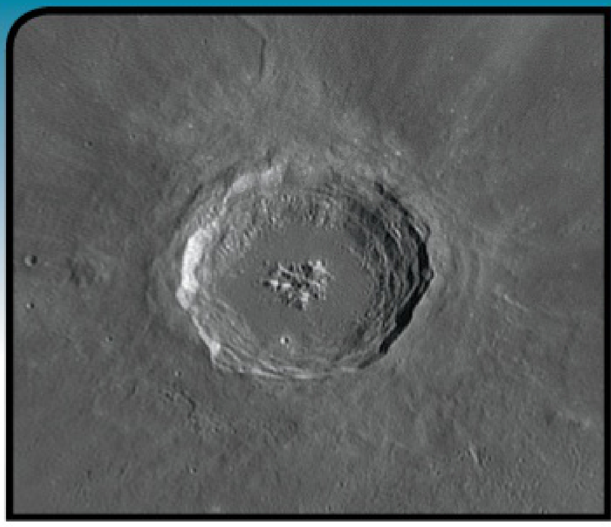
THE MOON OFFERS LOTS OF VISUAL TREATS when viewed through a telescope — even a small one. With that in mind, let's focus on First Quarter. This phase is easy to observe because it rises around noon and sets at midnight (one hour later if daylight saving time is in effect), so it's visible throughout the evening. If you head outdoors at sunset, just look due south.



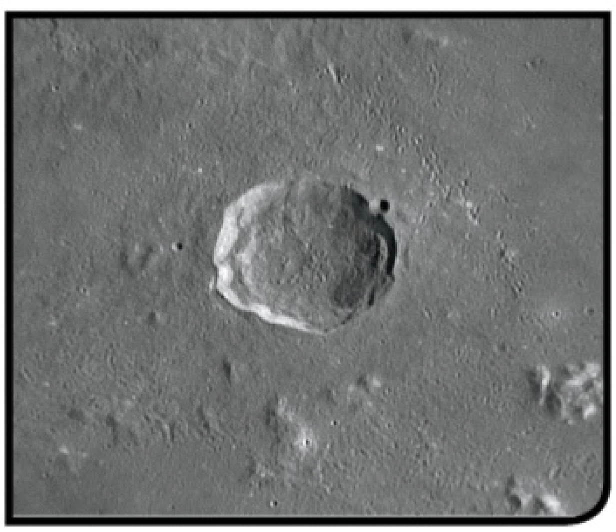
1 Vallis Alpes is a cleft that bisects the Montes Alpes range. The valley is narrow at both ends and wider along its middle. Look carefully for small details here. Can you see that the southern face is straighter than the northern side, which is slightly bowed and uneven? The more rugged edges of the valley lie at the narrow west-southwest end that cuts through the mountain range. ALL PHOTOS BY DAMIAN PEACH, UNLESS NOTED



2 Cassini Crater lies at the eastern end of Mare Imbrium. The flooded floor of the crater shows many impacts. The largest crater that sits entirely within the rim is Cassini A, just northeast of center. A hilly ridge runs from it to the southeast. Near the southwest rim is the smaller crater Cassini B.

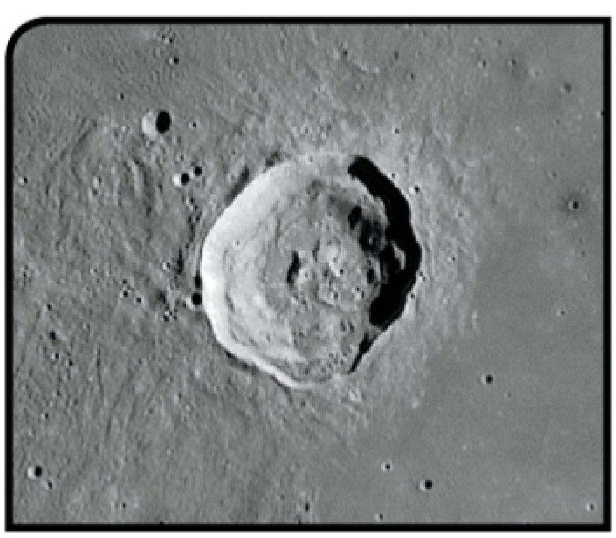


3 Aristillus is a prominent crater with a bright ray system. Use a low-power eyepiece and you'll see it extending for more than 370 miles (600 km). Then switch to high power and look carefully for the faint remains of a ghost crater off Aristillus' top left edge. It's almost buried by ancient lava flows.



4 Autolycus is a small impact crater just to the south of the more prominent Aristillus Crater. It has a faint impact-ray system extending outward, and some of the material crosses the floor of nearby Archimedes Crater.

6 Hipparchus is the degraded remnant of a lunar crater near the Moon's center. This ancient feature has been modified by subsequent impacts. Horrocks Crater lies entirely within its northeast rim. Halley Crater is attached to the south rim, and Hind Crater lies to the southeast. To the north-northeast is the bowl-shaped Pickering Crater, and lava-flooded Saunder Crater lies off the northeast rim.



5 Manilius Crater formed through an impact on the northeast edge of Mare Vaporum. It has a well-defined rim with a sloping inner surface that runs down to the ring-shaped mound along the base. The small interior crater is more reflective than the surroundings, and it appears bright when the Sun is overhead.

Why this phase?

First Quarter falls within the best times for viewing the Moon, when shadows are longer and lunar features stand out in sharp relief. The area where this is most evident lies along the terminator, the line dividing the light and dark portions of the Moon's surface. At First Quarter, the terminator shows where sunrise is occurring.

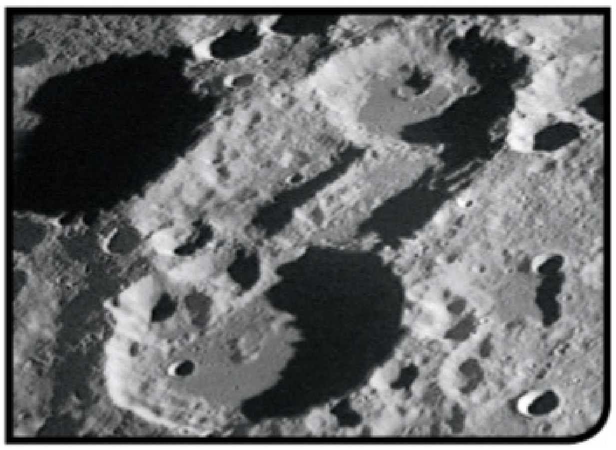
Along the terminator, you'll spot dots of light where mountaintops are high enough to catch sunlight but the surrounding lower terrain is still shrouded in shadow. On the floors of large craters, you can follow "wall shadows" cast by the sides of craters hundreds of feet high. All of these features change in real time, so in just a few hours, the differences can be striking.

Observing tips

For some observers, the First Quarter Moon appears too bright through a telescope. You can deal with this in several ways. You could use a neutral density filter, which is a (carefully made) dark piece of glass that screws into the bottom of an eyepiece. A similar device, a variable polarizing filter, lets you change the amount of light passing through it. Another way you can reduce the Moon's apparent brilliance is to turn on a white light behind you. The additional light suppresses the eyes' tendency to adapt to the dark, allowing you to use normal

7 Albategnius Crater is so large that lunar scientists often refer to it as a walled plain or a ring mountain. Look closely at the most prominent overlapping craters: Klein, which sits to the lower left in this image, and Albategnius B, just inside the northern rim at the top. Note that Albategnius' outer wall has a rough hexagonal shape.

8 Stöfler is a large impact crater located in the Moon's southern highlands. Look for Faraday Crater, which overlays its western edge. The rim of Stöfler is worn, but its outline remains intact except at Faraday. In a reverse of Manilius Crater, Stöfler's floor has a low reflectivity, making the crater easy to identify.



9 Heraclitus is a complex crater in the Moon's rugged southern highlands. Licetus Crater forms the northern end of the formation. Just to the east is Cuvier Crater, and due south is Lilius Crater. The entire formation is heavily worn, with features smoothed down by a long history of impacts.

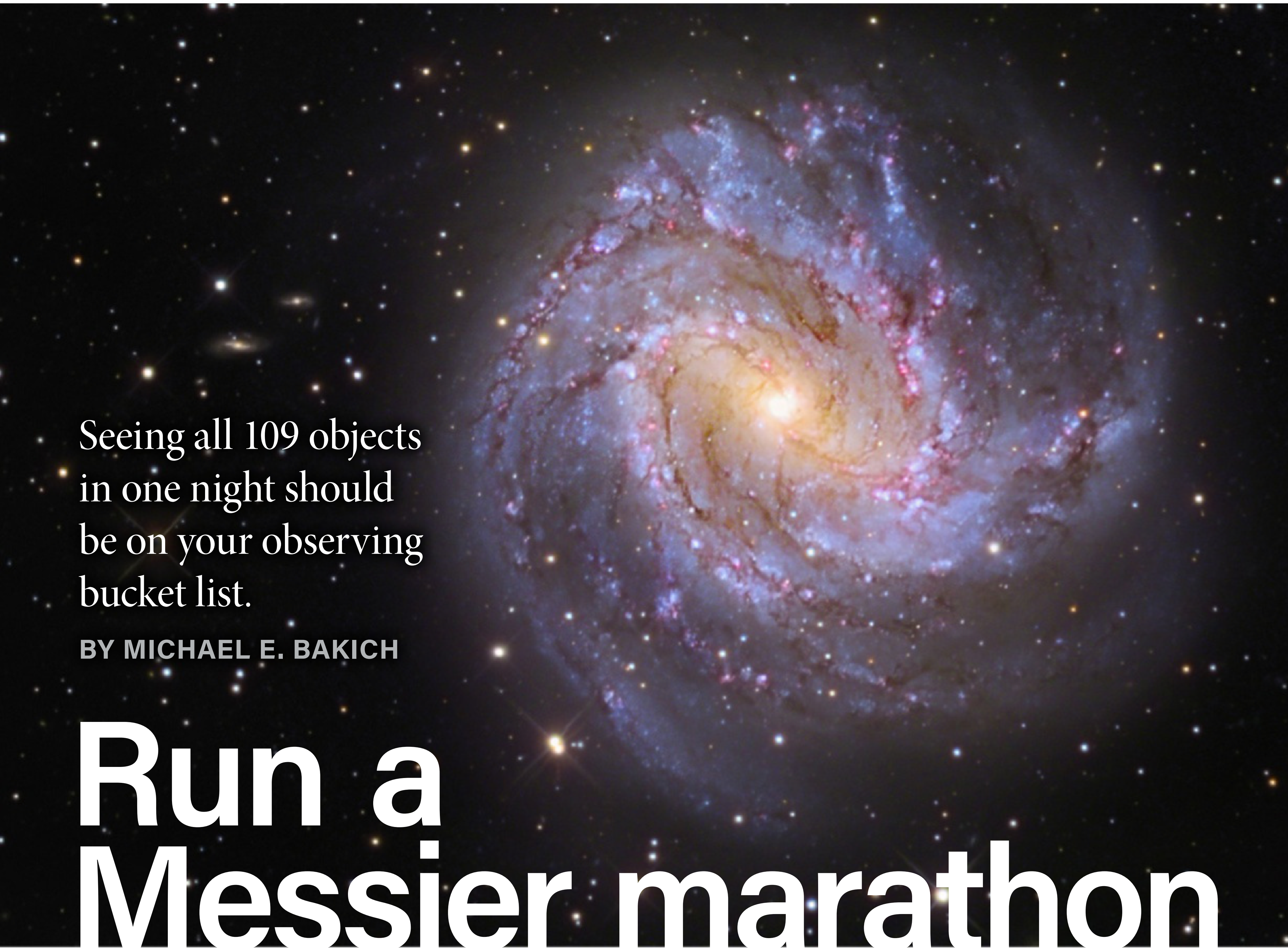
scotopic (daytime) vision, which is of much higher quality than dark-adapted photopic vision. Finally, you can use an aperture mask — a piece of cardboard that covers the front of your scope with a small hole cut in it — to turn your telescope into one of much smaller aperture.

All the features shown in the photos accompanying this story lie along the terminator around First Quarter. If you get a string of clear nights, view these features two or more evenings in a row. You'll be surprised at how different they appear after 24 hours. Compare what you see with the images.

As practical advice, sit while you observe. Try different eyepieces of increasing magnification until the image starts to deteriorate because of the atmosphere. Note any additional details that high powers make visible.

Remember, when you observe the Moon, there's nothing you need to do quickly. Take your time and relax. This is easy observing, so have fun.

Michael E. Bakich *is a contributing editor of* Astronomy *who points his 4-inch scope at the First Quarter Moon each month.*



Seeing all 109 objects in one night should be on your observing bucket list.

BY MICHAEL E. BAKICH

Run a Messier marathon

The Crab Nebula (M1) in Taurus is the only supernova remnant on Messier's list. ALL IMAGES: ADAM BLOCK/MOUNT LEMMON SKYCENTER/UNIVERSITY OF ARIZONA

ON YOUR MARK. GET SET …

Amateur astronomers across the world delight in the beginning of spring. Oh, sure, it means nights will be getting warmer (at least north of the equator), but, more importantly, the new season signals the start of the Messier marathon. Go!

Some history

Eighteenth-century French astronomer Charles Messier loved to hunt for comets. But as he tracked his prey, he occasionally would spot a fuzzy object through his small telescope. He'd get excited, thinking he had found a new comet, but then, after repeated observations, he'd notice the object didn't move against the background of stars like comets did.

As you might imagine, this ticked Messier off. He worried that other observers — who weren't as thorough with their follow-up observations — would report such sightings as comets. This frustration led him to create and publish a list of such "nuisance" objects, and he began to record his encounters with them.

His first find came during a search August 28, 1758, when Messier discovered a misty patch in Taurus. A comet? No. This was the first of his nonmoving objects, and it became the initial entry — M1 — in his catalog. Subsequent discoveries by Messier and others brought the final tally of objects to 109, the catalog we recognize today.

In total, Messier discovered 41 of the

ABOVE: The Hercules Cluster (M13) is a favorite target for amateur astronomers.

LEFT: The Southern Whirlpool Galaxy (M83) in Hydra is one of the finest barred spirals in the sky.

objects — the most by any discoverer — through a variety of telescopes. Because all the instruments he used were small and of questionable quality, he found only large, bright objects. This works to the advantage of today's observers, because even a medium-sized modern scope can really make these big objects pop.

Running the marathon

The 109 targets in Messier's catalog are not distributed evenly across the sky. That's good, because if they were, there would never be a time when you could see them all during a single night. Instead, one or more would always be too close to the Sun. Sagittarius holds 15 of the objects, the most of any constellation. Virgo is next (11), followed by Coma Berenices (eight), and Ophiuchus and Ursa Major (seven each).

The most important point about this uneven distribution is that none of the targets resides in western Aquarius or eastern Pisces. So, when the Sun passes through that area in its yearly apparent trip through the constellations of the zodiac, it burns far from any M object. That means observers have a chance to see them all in a single night.

Years ago, contributing editor Tom Polakis calculated the window of opportunity for a complete Messier marathon. He defined the beginning of the observing window as the date when globular cluster M30 in Capricornus is high enough to spot in a dark sky. Working

The Trifid Nebula (M20) in Sagittarius lies low in the sky for many observers, but it's well worth finding.

The Blackeye Galaxy (M64) in Coma Berenices is an easy catch through a small scope.

MARATHON SEARCH ORDER

If a marathon is in your future, use the list below (and a good star chart) to try this entertaining event, preferably with friends. The list order is best for a midnorthern-latitude site. People in more southerly locations will have an easier time viewing some objects.

Start as soon as twilight fades enough for you to identify more than just the bright stars. Locate spiral galaxies M77 and M74 before you move on because they'll set soon after it gets dark. In the morning, M30 will be your challenge object. Good luck!

Messier Number	NGC Number	Constellation	Type	Magnitude
M77	1068	Cetus	Gal	8.9
M74	628	Pisces	Gal	8.5
M33	598	Triangulum	Gal	5.7
M31	224	Andromeda	Gal	3.4
M32	221	Andromeda	Gal	8.2
M52	7654	Cassiopeia	OC	6.9
M103	581	Cassiopeia	OC	7.4
M76	650–1	Perseus	PN	10.1
M34	1039	Perseus	OC	5.2
M45	-	Taurus	OC	1.5
M79	1904	Lepus	GC	7.7
M42	1976	Orion	EN	3.7
M43	1982	Orion	EN	6.8
M78	2068	Orion	RN	8.0
M1	1952	Taurus	SNR	8.0
M35	2168	Gemini	OC	5.1
M37	2099	Auriga	OC	5.6
M36	1960	Auriga	OC	6.0
M38	1912	Auriga	OC	6.4
M41	2287	Canis Major	OC	4.5
M93	2447	Puppis	OC	6.2
M47	2422	Puppis	OC	5.7
M46	2437	Puppis	OC	6.1
M50	2323	Monoceros	OC	5.9
M48	2548	Hydra	OC	5.8
M44	2632	Cancer	OC	3.1
M67	2682	Cancer	OC	6.0
M95	3351	Leo	Gal	9.7
M96	3368	Leo	Gal	9.2
M105	3379	Leo	Gal	9.3
M65	3623	Leo	Gal	8.8
M66	3627	Leo	Gal	9.0
M81	3031	Ursa Major	Gal	6.9
M82	3034	Ursa Major	Gal	8.4
M97	3587	Ursa Major	PN	9.9
M108	3556	Ursa Major	Gal	10.0
M109	3992	Ursa Major	Gal	9.8
M40	Win4	Ursa Major	DS	9.0/9.6
M106	4258	Canes Venatici	Gal	8.3
M94	4736	Canes Venatici	Gal	8.2
M63	5055	Canes Venatici	Gal	8.6
M51	5194	Canes Venatici	Gal	8.4
M101	5457	Ursa Major	Gal	7.9
M102	5866	Draco	Gal	10.0
M53	5024	Coma Berenices	GC	7.7
M64	4826	Coma Berenices	Gal	8.5
M3	5272	Canes Venatici	GC	5.9
M98	4192	Coma Berenices	Gal	10.1
M99	4254	Coma Berenices	Gal	9.9
M100	4321	Coma Berenices	Gal	9.3
M85	4382	Coma Berenices	Gal	9.1
M84	4374	Virgo	Gal	9.1

with the premise that the object has to be at least at an altitude of 2° for observers to see it, Polakis calculated the Sun's altitude at that time, as well as its distance from M30. On the evening end, the limiting object is spiral galaxy M74 in Pisces. The inability to see it through twilight's glare defines the conclusion of the observing window. Polakis' numbers are for Phoenix (33° north latitude), and they get more favorable the more southerly your observing site, particularly for M30. In this calculation, the season begins March 17 and ends April 3.

So, can you see them all? Absolutely. Many people have viewed all the Messier objects in one night. Some observers, however, seek more of a challenge, like trying to see as many through as small a telescope (or binoculars) as possible. I once ran a Messier marathon using 7x50 binoculars. The night was partly cloudy, but the air was steady, so I was able to log 75 of the 109 targets. I'd guess that, on a better night, I could have seen 90.

If you're about to embark on your first marathon, don't worry about such things. As long as you have a high-quality 3-inch (or larger) telescope, you can see all the Messier objects from a dark site on a night when the atmosphere is steady.

Also, remember that your goal is to

Bode's Galaxy (M81) is a showpiece that you'll find near the Big Dipper in Ursa Major.

Messier Number	NGC Number	Constellation	Type	Magnitude
M86	4406	Virgo	Gal	8.9
M87	4486	Virgo	Gal	8.6
M89	4552	Virgo	Gal	9.7
M90	4569	Virgo	Gal	9.5
M88	4501	Coma Berenices	Gal	9.6
M91	4548	Coma Berenices	Gal	10.1
M58	4579	Virgo	Gal	9.6
M59	4621	Virgo	Gal	9.6
M60	4649	Virgo	Gal	8.8
M49	4472	Virgo	Gal	8.4
M61	4303	Virgo	Gal	9.6
M104	4594	Virgo	Gal	8.0
M68	4590	Hydra	GC	7.6
M83	5236	Hydra	Gal	7.5
M5	5904	Serpens	GC	5.7
M13	6205	Hercules	GC	5.3
M92	6341	Hercules	GC	6.5
M57	6720	Lyra	PN	8.8
M56	6779	Lyra	GC	8.4
M29	6913	Cygnus	OC	6.6
M39	7092	Cygnus	OC	4.6
M27	6853	Vulpecula	PN	7.3
M71	6838	Sagitta	GC	8.0
M107	6171	Ophiuchus	GC	7.8
M12	6218	Ophiuchus	GC	6.8
M10	6254	Ophiuchus	GC	6.6
M14	6402	Ophiuchus	GC	7.6
M9	6333	Ophiuchus	GC	7.8
M4	6121	Scorpius	GC	5.4
M80	6093	Scorpius	GC	7.3
M19	6273	Ophiuchus	GC	6.8

Messier Number	NGC Number	Constellation	Type	Magnitude
M62	6266	Ophiuchus	GC	6.7
M6	6405	Scorpius	OC	4.2
M7	6475	Scorpius	OC	2.8
M11	6705	Scutum	OC	5.3
M26	6694	Scutum	OC	8.0
M16	6611	Serpens	EN	6.0
M17	6618	Sagittarius	EN	6.0
M18	6613	Sagittarius	OC	6.9
M24	6603	Sagittarius	SC	2.5
M25	IC 4725	Sagittarius	OC	4.6
M23	6494	Sagittarius	OC	5.5
M21	6531	Sagittarius	OC	5.9
M20	6514	Sagittarius	EN	6.3
M8	6523	Sagittarius	EN	3.0
M28	6626	Sagittarius	GC	6.9
M22	6656	Sagittarius	GC	5.2
M69	6637	Sagittarius	GC	7.4
M70	6681	Sagittarius	GC	7.8
M54	6715	Sagittarius	GC	7.2
M55	6809	Sagittarius	GC	6.3
M75	6864	Sagittarius	GC	8.6
M15	7078	Pegasus	GC	6.0
M2	7089	Aquarius	GC	6.3
M72	6981	Aquarius	GC	9.2
M73	6994	Aquarius	OC	8.9
M30	7099	Capricornus	GC	6.9

Key: DS = Double star; EN = Emission nebula; Gal = Galaxy; GC = Globular cluster; OC = Open cluster; PN = Planetary nebula; RN = Reflection nebula; SC = Star cloud; SNR = Supernova remnant

see all the Messier objects in one night. Toward that end, you might hear someone mutter that a go-to drive (one that finds and tracks celestial objects) breaks the rules. Wait. What rules? Use your telescope's computer. Then, for your 10th-anniversary marathon, you can try to find them by star hopping with charts.

Why marathon?

After more than 30 years of Messier marathons, there's one approach I've never tried: doing it alone. To guarantee you'll enjoy the marathon, make it a social event. Every astronomy club with a dedicated cadre of observers schedules a Messier marathon. Hard-core amateurs hold it as close to New Moon as possible, whenever that falls in early spring. Most clubs, however, schedule their marathon for the Friday or Saturday night (or both) nearest New Moon.

In 2020, New Moon in March falls on Tuesday the 24th. Ideally, we'd go out that night and see all 109 objects. Many of us, however, must work the next day, so our best options become either the preceding Saturday, March 21, or the following Friday, March 27. Only because March 21 comes first, I suggest you aim for that date, and keep the 27th (or 28th) as your "bad weather" backup date.

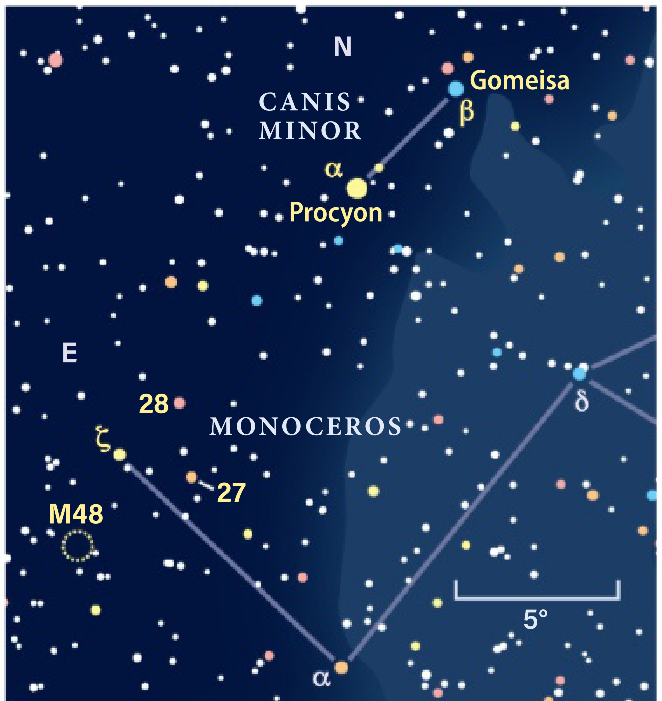
Above all, a Messier marathon is meant to be fun — a time when observers come together with a common purpose. And, as an added bonus, being with a group might get you thinking about a new equipment purchase.

If you don't see all the Messier objects this year, whether it's due to your schedule or clouds, 2021 has no New Moon within the marathon window. You'll instead have to wait for 2022, when New Moon falls on April 1 (no fooling). So, I wish you all clear skies this month.

Contributing Editor **Michael E. Bakich** *still has a blast running Messier marathons.*

A month of change

Canis Minor points to an array of unusual stars.



Although it's a small constellation, Canis Minor the Little Dog contains interesting stars, including its brightest, Procyon.
ASTRONOMY: ROEN KELLY

March is a month of transition, here on Earth as well as in the night sky. As the Sun moves northward along the ecliptic, the days are getting longer and the chill of winter begins to abate.

As Orion marches toward the western horizon in pursuit of Taurus, his attending small dog, Canis Minor, lags behind. Canis Minor is one of those constellations that makes me wonder how anyone could imagine seeing the namesake figure among its stars. After all, Canis Minor is drawn from only two: Procyon [Alpha (α) Canis Minoris] and Gomeisa [Beta (β) Canis Minoris]. A small dog from two stars? Maybe a hot dog, but that's the best I can do.

Nicknamed the Little Dog Star, **Procyon** ranks eighth among the sky's brightest. Its prominence is primarily due to its location just 11.4 light-years away. Through our binoculars, it gleams pure white, a spectral class F5IV–V. That's a shorthand way of saying that Procyon is about 40 percent more massive and 10 percent hotter than our Sun, and also that it is a star in transition. Procyon's core is rapidly running out of fusible hydrogen, causing it to leave the main sequence and transition to the subgiant portion of the Hertzsprung-Russell diagram. Procyon is also orbited by a white dwarf known as Procyon B. There is no hope of seeing it through our binoculars. Even through the largest amateur telescopes, Procyon B is a difficult challenge.

Canis Minor is one of those constellations that makes me wonder how anyone could imagine seeing the namesake figure among its stars.

At third magnitude, **Gomeisa** appears much less impressive than Procyon. If you are observing from a heavily light-polluted area, you might need binoculars just to see it. But the Small Dog's Beta star would rank "alpha" if placed side by side with Procyon; its diminutive appearance is due to being 15 times farther away. Gomeisa is classified as spectral type B8V, a massive blue stellar inferno located to the far upper left of the HR diagram's main sequence. Like our Sun, it is happily fusing hydrogen into helium in its core. Maintaining its energy output, however, comes with a cost: Gomeisa's life span may be only 10 million years versus our more judicious Sun's projected 10 billion.

While the small dog leaves something to be desired visually, its breed is clear. It's a pointer. How do I know? Because a line extending southeast from Gomeisa through Procyon points to an underappreciated open cluster, **M48**. Follow the pointer for about 11°, or about two binocular fields, and you'll come to an equilateral triangle formed by Zeta (ζ), 27, and 28 Monocerotis. Look half a field south-southeast of Zeta to see a fuzzy patch of light. That's our target.

For nearly two centuries, M48 was considered "lost." History shows that Charles Messier discovered M48 on February 19, 1771. After describing it in his log as a "cluster of very [faint] stars, without nebulosity; this cluster is at a short distance from the three stars that form the beginning of the Unicorn's tail [Zeta, 27, and 28 Monocerotis]," he noted its position and moved on. From this, he later calculated its celestial coordinates — and goofed. Messier mistakenly placed his discovery 5° north of its actual location. Before it was officially found again, it was independently discovered by others and awarded the designation NGC 2548. The "Case of the Missing Cluster" was finally cracked in 1959 by Theodore F. Morris, a member of the Royal Astronomical Society of Canada, and confirmed a year later by Harvard University astronomer Owen Gingerich. Morris noted that NGC 2548 had the same right ascension as the missing Messier object, but that its declination was off. After examining records at Paris Observatory, Gingerich confirmed this assertion, and M48 was "found."

More than 80 stars populate M48, with some studies including more than 320 stars after factoring in outliers. Based on the types of stars found within, astronomers estimate M48's age at 300 million years. Collectively, they lie about 2,500 light-years away.

M48 is a splendid target for binoculars. The cluster's densest portion covers about half a degree, but by including stragglers, the full span nearly doubles in size. Several 8th- and 9th-magnitude cluster stars immediately shine through the mist created by fainter suns. My 10x50s reveal a centralized knot of stars, while my 16x70s add short threads of fainter points. Look carefully, and you might also notice that a couple of those stars display hints of pale yellow or orange.

Do you have a favorite binocular object that you would like to share with the rest of us? Contact me through my website, philharrington.net. Remember, two eyes are better than one.

BY PHIL HARRINGTON
Phil is a longtime contributor to Astronomy *and the author of many books.*

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Picking a beginner's guide

Your key to unlocking the night sky awaits.

A sampling of the author's personal collection of beginner guidebooks is seen on display at his home. Though there are numerous guides aimed at beginners, the four examples shown above are a great introduction for any budding backyard astronomer. GLENN CHAPLE

BY GLENN CHAPLE
Glenn has been an avid observer since a friend showed him Saturn through a small backyard scope in 1963.

When it comes to putting together a list of favorites, whether it be restaurants, movies, or TV shows, I always run into trouble if I try to limit myself to a specific number. In putting together a "Top 10" list, for example, I invariably find a No. 11 that's just as good as No. 9 or No. 10.

This is the problem I faced as I set out to write this month's column, which highlights guidebooks for the backyard astronomer. By limiting myself to those I could adequately describe in a one-page article, I'd be sure to leave out some goodies. So, with a little trepidation, I'll begin with a rundown on guides directed toward the novice skygazer (or the veteran who's looking to brush up).

Foremost in this genre is *365 Starry Nights: An Introduction to Astronomy for Every Night of the Year* by Chet Raymo (Prentice Hall, 1982). If your knowledge of astronomy is nil, this book is an essential starting point. As the name indicates, *365 Starry Nights* is a night-by-night astronomy primer that helps the reader identify what's on display in the current night sky, while also adding information on basic cosmology and astronomical history. Entries for March include: an in-depth look at the constellations Cancer, Hydra, and Lynx; an intro to stellar classification; and historical notes on the Messier catalog and Olbers' paradox.

Your next step is to explore Terence Dickinson's *NightWatch: A Practical Guide to Viewing the Universe* (Firefly Books, fourth edition, 2006). This handbook covers the organization of the universe, the fundamentals of skygazing, astronomical equipment (binoculars, telescopes, and accessories), and tips on observing everything from meteors and aurorae to distant galaxies — in other words, pretty much anything a fledgling backyard astronomer would need to know.

Those two guides alone would suffice to get any newcomer started, but Dickinson also has another handbook, co-authored with Alan Dyer. Not only does their *The Backyard Astronomer's Guide* (Firefly Books, revised edition, 2002) mesh nicely with *NightWatch*, it adds enough advanced material to help the beginner transition to intermediate status. Part 1 deals with equipment, from binoculars and telescopes to eyepieces and accessories. Part 2 handles the basics of observing — naked eye, as well as with optical aid. And part 3 covers advanced tips on digital astrophotography, go-to telescopes, computer-related aids, and telescope maintenance. *The Backyard Astronomer's Guide* is regularly updated on its website: www.backyardastronomy.com.

I'm going to throw one more beginner-oriented guide into the mix. *Celestron Sky Maps* (Hubbard Scientific, 2007) combines two essential tools for the backyard astronomer: a planisphere and a star atlas. A planisphere works like the Star Dome in the middle of each issue of *Astronomy*, except that it can be adjusted to any date and time of the year. While a planisphere helps you locate a constellation in the sky, a star atlas provides a detailed look at that constellation. The front cover of *Celestron Sky Maps* is a glow-in-the-dark planisphere, while the main body is an eight-chart atlas arranged by season. Facing each chart is a table describing key deep-space objects plotted on the chart. The guide is printed on heavy cardstock with a protective overcoat for outdoor use, and it's also spiral bound to allow the charts to lie flat.

***Celestron Sky Maps* combines two essential tools for the backyard astronomer: a planisphere and a star atlas.**

The guides in this article can be purchased at your local bookstore or ordered online. Remember, picking up a used edition is always a good idea — it's more environmentally friendly, and usually costs less.

Alas, as I feared, I've run out of room and I've only discussed beginner's guides. Next month, we'll look at guides geared for the intermediate and advanced skygazer.

Questions, comments, or suggestions? Email me at gchaple@hotmail.com. Next month: guides that list sky objects for binoculars and telescope. Clear skies!

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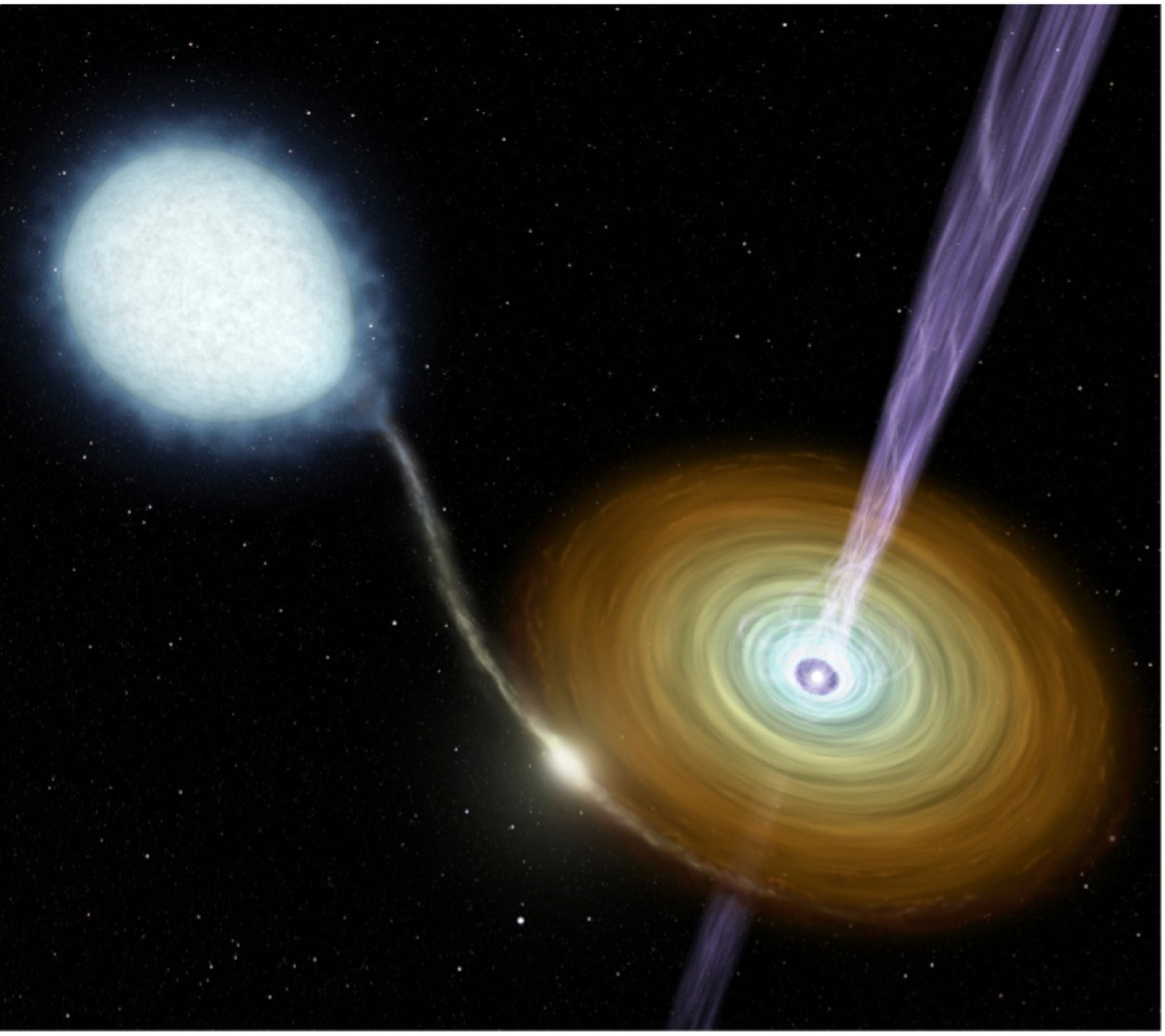


It is straightforward to calculate the mass of a neutron star in a binary system, depicted in this artist's concept (the neutron star is on the right, pulling material off its companion star at left). By watching the objects orbit each other, astronomers can use Kepler's laws of motion to derive their mass. NASA/JPL-CALTECH/R. HURT (SSC)

Weighing black holes

Q HOW DO ASTRONOMERS CALCULATE THE MASS OF A NEUTRON STAR OR BLACK HOLE?

Shobha Kaicker
Mississauga, Ontario

A Astronomers can calculate mass in several ways. The simplest is when the object is part of a binary system. Regardless of the objects in the binary — two stars, a star and a neutron star, a star and a black hole, et cetera — their orbits follow Kepler's laws of motion, which allow a scientist to calculate mass based on the speeds of the objects and the size of their mutual orbit. Additionally, when two objects such as neutron stars or black holes merge, the gravitational waves they produce tell astronomers the masses of the original objects, as well as the mass of the result their merger leaves behind.

But what about a lone neutron star or black hole? A single neutron star may give itself away as a pulsar. Pulsars are spinning neutron stars beaming out intense radiation along their poles. If these narrow beams happen to point at Earth, astronomers can identify the source as a neutron star. The signals from a pulsar are regularly spaced as the star spins. And some pulsars glitch, which makes them temporarily speed up. Astronomers believe glitches are caused by interactions between material from the neutron star's core and its crust. Tracking a glitch as it occurs can reveal information about the star's internal temperature. Work published in *Science Advances* in 2015 suggests that if researchers know the age of the neutron star, they can use glitches to measure the star's current internal temperature and compare it with a model of what the neutron star's interior should look like. The model, in turn, allows researchers to calculate the star's mass based on its temperature and age.

While it's not possible to accurately calculate the mass of a lone stellar-mass black hole created by the death of a single star, it is possible to calculate the mass of a galaxy's central supermassive black hole. That's because astronomers have observed a link between the mass of a supermassive black hole and the mass of the spheroidal component — the bulge — of the galaxy around it. There is also a link between the motion of the stars in a galaxy's bulge and the mass of its supermassive black hole. So, astronomers can measure one or both of these quantities to derive the mass of a galaxy's central supermassive black hole.

In the case of the Milky Way's supermassive black hole, however, researchers observed the motion of stars around the object over the course of years. This allowed them to use Kepler's laws to measure its mass: 4.3 million solar masses.

Alison Klesman
Associate Editor

Q | IF PHOTONS HAVE NO MASS, HOW CAN THEY PROPEL SOLAR SAILS LIKE THE PLANETARY SOCIETY'S LIGHTSAILS?

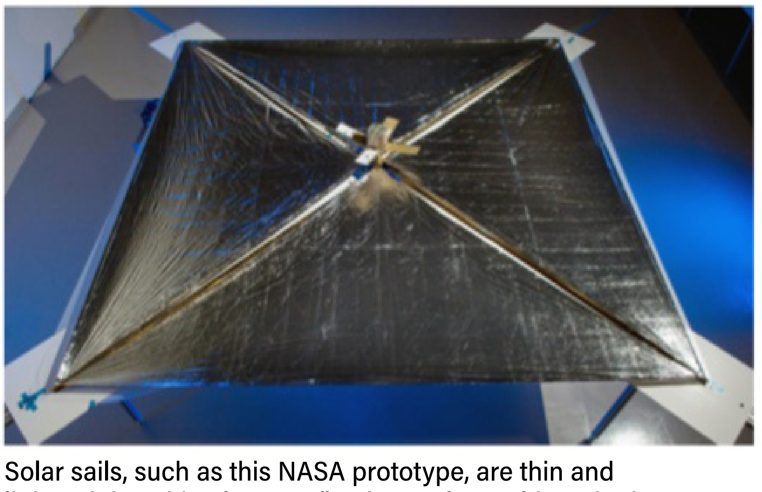
Doug Kaupa
Council Bluffs, Iowa

A | Photons don't have mass, but they do have momentum, which is energy associated with motion. If a photon strikes something, it can give some of its momentum to the object it hits. In the case of a solar sail, when light hits the sail's reflective surface, it bounces off, transferring some of the energy associated with its initial motion to the sail. This force is called radiation pressure, and it pushes the sail slightly in the direction the photon was traveling before it bounced off.

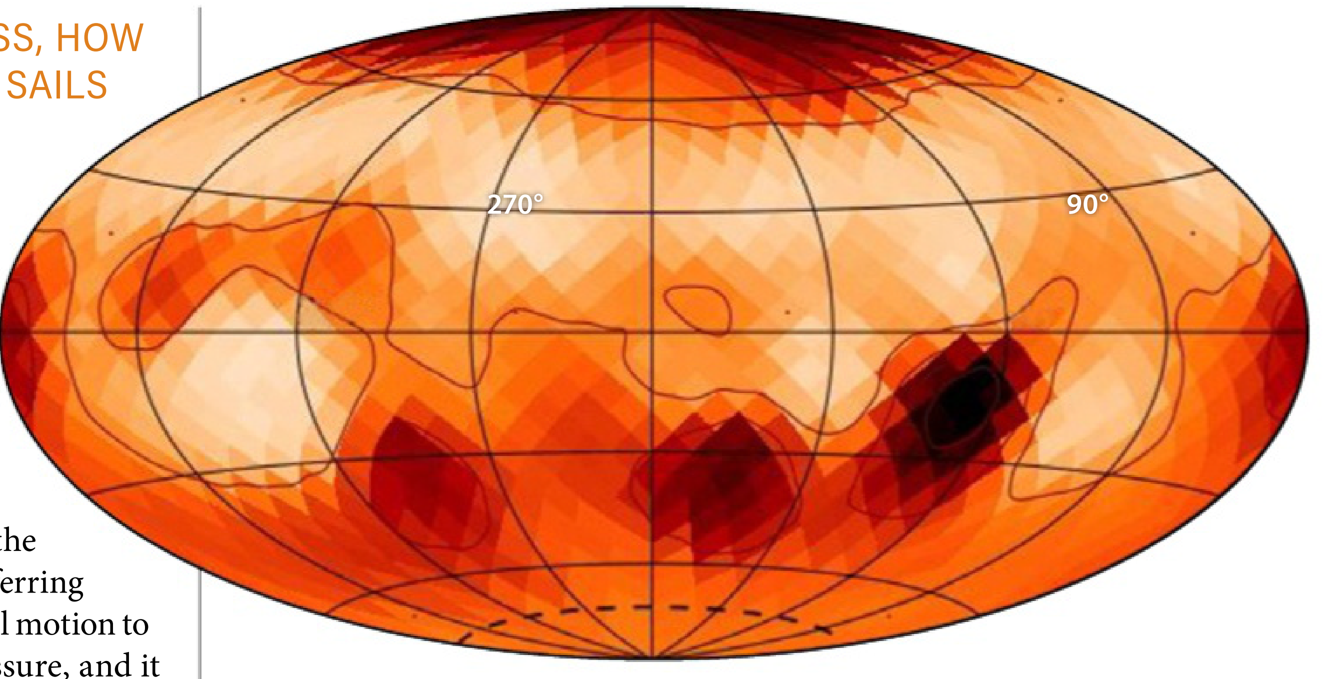
Although the energy transferred by a single photon is tiny, there is no friction in the vacuum of space. Each time a photon strikes the solar sail, it gains slightly more energy. The LightSail design is about 344 square feet (32 square meters) in size, compared to its width of only 0.0002 inch (0.00051 centimeter). These dimensions ensure the sail is both lightweight and has a large area to allow many photons to hit it at once. The Planetary Society calculated that its current LightSail mission, LightSail 2, can capture enough momentum from sunlight to accelerate about 0.0023 inch (0.0058 cm) per second, each second. After a month, this acceleration would boost the sail's speed to nearly 341 mph (550 km/h).

Radiation pressure can affect interplanetary dust and even small objects, such as asteroids, over time. But radiation pressure also diminishes with distance from the Sun, so the farther an object is from our star, the smaller the radiation pressure it feels, until this force becomes negligible.

Alison Klesman
Associate Editor



Solar sails, such as this NASA prototype, are thin and lightweight, with a large, reflective surface. Although photons have no mass, they carry momentum; when a photon bounces off a solar sail, some of its momentum is transferred to the sail, which pushes the sail forward. NASA/MSFC/D. HIGGINBOTHAM



In 2016, astronomers combined light from six telescopes to image the star Zeta (ζ) Andromedae. Several dark starspots are visible on its surface at midlatitudes, as well as one at the pole. Based on Zeta Andromedae's radius, which is 15 times larger than the Sun's, the spots nearer the equator are about the size of our star. ROETTENBACHER ET AL.

Q | HAVE SUNSPOTS BEEN OBSERVED ON OTHER STARS?

Peter Haik
Berea, Kentucky

A | Yes, astronomers have seen sunspots — in this case, called starspots — on other stars.

Sunspots appear as dark spots on the Sun because they are areas where the temperature is cooler than the surrounding gas. They're regions where the Sun's magnetic field extends outward from the surface, which reduces the area's temperature. Because this phenomenon is not limited to the Sun, it makes sense that such spots would occur on other stars.

And, in fact, the Kepler Space Telescope, which was designed to measure tiny changes in a star's brightness over time, often caught starspots during its mission. Kepler watched stars to look for telltale dips in brightness that occur when a planet crosses in front of the star from the telescope's viewpoint. But a large starspot can cause a similar dip in brightness. A study published in January 2019 in *The Astrophysical Journal*, led by Kosuke Namekata at Kyoto University in Japan, identified and tracked 56 starspots from a sample of more than 5,000 Sun-like stars that Kepler observed.

Alternatively, astronomers have seen some starspots directly. Beyond the Sun, this is only possible with nearby or giant stars that are imaged using a technique called interferometry. This technique combines images from multiple telescopes to create a virtual telescope much larger than its individual parts. Only about 20 stars have been imaged this way, including Antares, Betelgeuse, and Regulus. In these images, darker starspots are often visible. Understanding the activity of starspots on other stars ultimately helps astronomers better understand the behavior and evolution of all stars.

Alison Klesman
Associate Editor

SEND US YOUR QUESTIONS

Send your astronomy questions via email to askastro@astronomy.com, or write to Ask Astro, P.O. Box 1612, Waukesha, WI 53187. Be sure to tell us your full name and where you live. Unfortunately, we cannot answer all questions submitted.

Cosmic portraits

1. TWO THUMBS UP
On August 9, 2019, two comets — 260P McNaught and ASASSN (C/2018 N2) — appeared to cross tails in the constellation Aries the Ram. At the time, each of these celestial visitors to our inner solar system glowed at magnitude 12.
• Gerald Rhemann

2

3

2. MAIDENS AT NIGHT
The replica of the Erechtheion at Karyes, Greece, provided the foreground to frame six hours of Earth's rotation, as shown by the apparent motion of the stars. To create this image, the photographer combined 690 exposures of 30 seconds each.
• Anthony Ayiomamitis

3. BRRRR!
The Milky Way stretches from horizon to horizon above Kouchibouguac National Park in New Brunswick, Canada, in this 11-part panorama. The imager stood in the middle of the frozen river. Deep cracks in the ice are visible beneath the snow. *• Barry Burgess*

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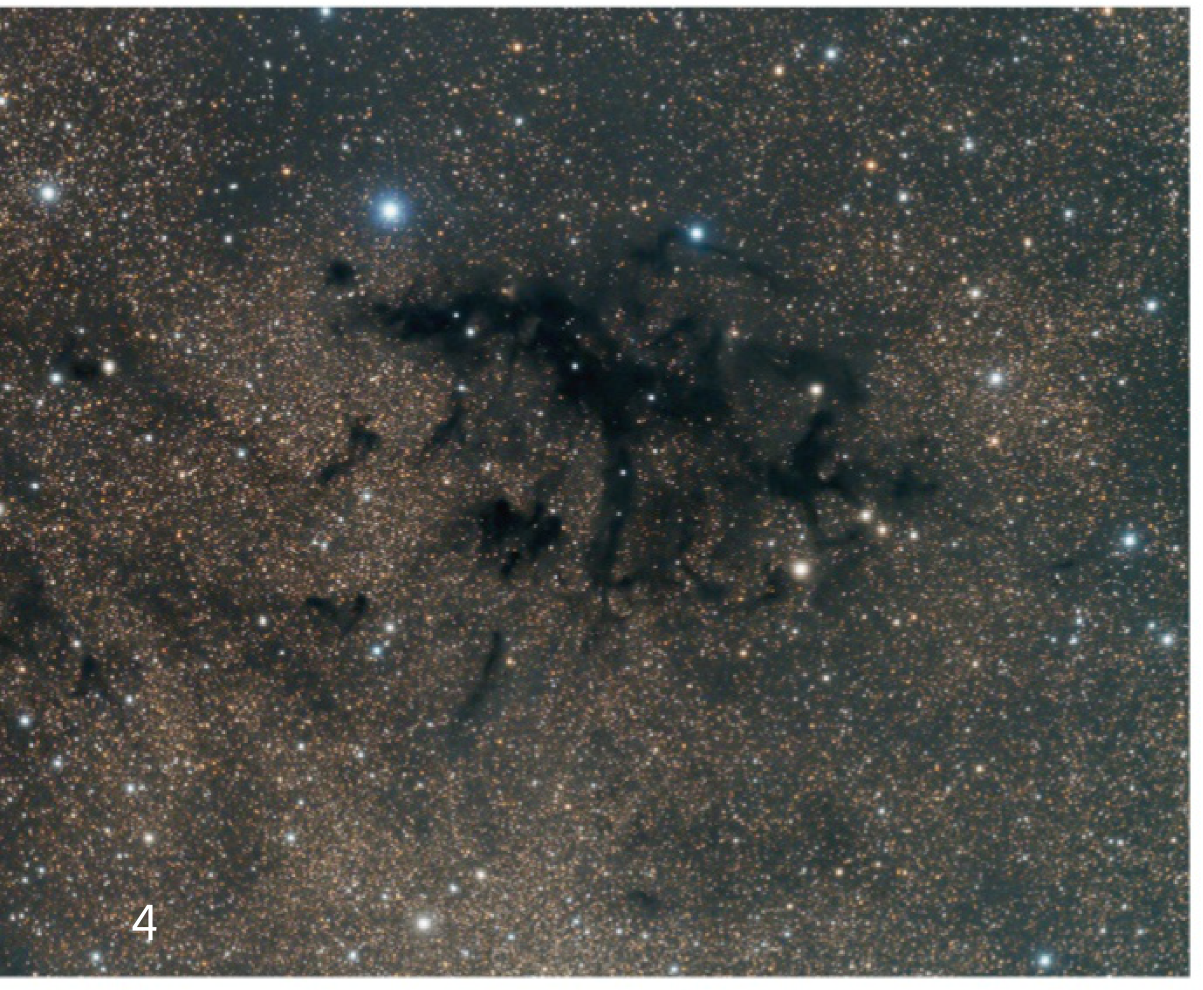
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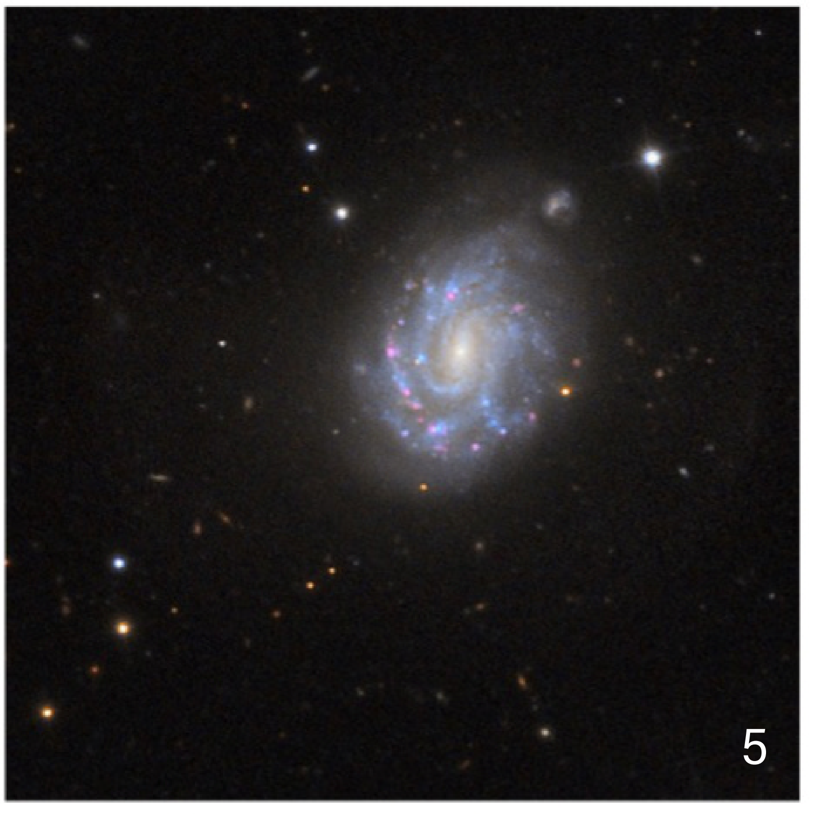
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4. DARK FINGERS
LDN 673 is a complex of dark nebulosity in the constellation Aquila the Eagle. This material, a combination of dust and cold hydrogen, blots out the light of stars and nebulae behind it. Eventually, it will collapse to form stars.
• Michael Israel

5. NOTABLY OBSCURE
NGC 4390 is a spiral galaxy in the constellation Virgo the Maiden. It lies 80 million light-years away. The faint halo (with some shell-like enhancements) surrounding this galaxy is due to galactic star streams: Some other small galaxy was torn apart, and now its pieces form NGC 4390's halo of stars.
• Adam Block/Mount Lemmon SkyCenter/ University of Arizona

6. NICE CATCH
A Perseid meteor streaks by the Andromeda Galaxy (M31) on the night of August 12, 2019, from Soomaa National Park in Estonia. The photographer took and stacked 255 exposures of M31 at 30 seconds each; one captured the meteor.
• Viljam Takis


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MARKETPLACE

INDEX *of* ADVERTISERS

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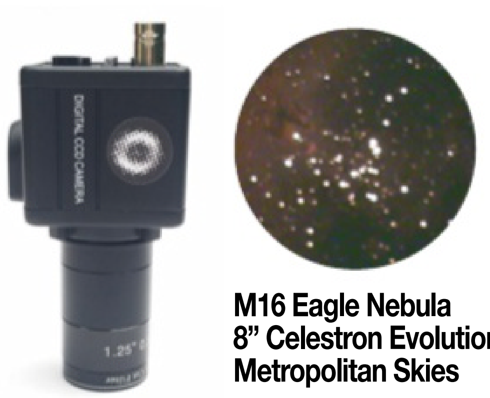


A BLAST FROM THE DISTANT PAST

The stars at night may seem eternal, but none can survive forever. A once-vibrant star in the Large Magellanic Cloud (LMC) — the Milky Way's biggest satellite galaxy — met its end in a titanic explosion that lit up Earth's southern sky a few thousand years ago. The resulting supernova remnant, LMC N63A, now spans some 50 light-years. This image combines observations from two orbiting observatories: The Hubble Space Telescope captured visible light (brown and tan) from several irregularly shaped clouds of gas and dust heated by the explosion's shock waves, and the Chandra X-ray Observatory recorded X-rays (red, green, and blue) from multimillion-degree gas swept up by the expanding shock waves.

ENHANCED IMAGE BY JUDY SCHMIDT (CC BY-NC-SA), BASED ON CHANDRA (NASA/CXC/SAO) AND HUBBLE (NASA/STScI) DATA

May 2020
Jupiter and Saturn on the prowl

Although **Venus** has dominated our early evening sky for the past several months, its days are numbered. The brilliant planet disappears in twilight by late May, but not before putting on a grand display. In early May, you can find Venus hanging low in the northwest as darkness falls. Gleaming at magnitude –4.7, the planet stands out despite lying just 10° high 45 minutes after sundown. Its altitude dips to 6° at the same time relative to sunset in mid-May.

Telescopes of all sizes offer stunning views. Because the Sun illuminates Venus from behind, it shows a lovely crescent shape. On May 1, the planet's disk spans 39" but appears only one-quarter lit. Two weeks later, on the evening of the 15th, Venus' diameter has swollen to 49" while the Sun illuminates just 12 percent of its Earth-facing hemisphere.

The solar system's two largest planets come on the scene later in the evening. **Jupiter** pokes above the eastern horizon shortly after 10 P.M. local time in early May and some two hours earlier by month's end. **Saturn** follows its bigger brother closely all month, rising less than a half-hour later.

Jupiter resides in eastern Sagittarius, not far from the Archer's border with Capricornus the Sea Goat. Shining at magnitude –2.4 — a magnitude brighter than the night sky's brightest star, Sirius — the gas giant rules the late evening sky. It looks just as impressive through a telescope. The planet's disk measures 43" across in mid-May and should show a wealth of detail in its dynamic atmosphere. Look in particular for two parallel dark belts, one on either side of a brighter zone that coincides with the jovian equator. And it's always fun to follow the changing positions of Jupiter's four bright moons: Io, Europa, Ganymede and Callisto.

The ringed planet graces far western Capricornus. Glowing at magnitude 0.5, it appears less than 10 percent as bright as its planetary companion. Still, that makes it brighter than all but a handful of stars visible in May's late evening sky.

The proximity of Jupiter and Saturn makes it easy to swing your telescope between the two. Although you won't be disappointed with your view of Jupiter, Saturn steals the show. The more distant world boasts a 17"-diameter disk surrounded by a glorious ring system that spans 39" and tilts 21° to our line of sight. Modest apertures also bring four or five saturnian satellites into view.

Don't go to bed after you've satisfied your giant planet cravings, because **Mars** will join them on the celestial stage within a couple of hours. The Red Planet heads eastward from Capricornus into Aquarius during May. The ruddy world brightens from magnitude 0.4 to 0.0 this month, far outshining the dim stars that call these constellations home.

Mars will put on a great show later this winter and spring, but it is still worth viewing through a telescope now. By the end of May, the diminutive planet's disk spans 9". Its southern hemisphere continues to tip toward Earth, so the white south polar cap should show up well during moments of good seeing.

After **Mercury** passes on the far side of the Sun from our viewpoint May 4, it slowly climbs into view after sunset. Those with sharp eyesight might glimpse it low in the northwest by month's end. On the 31st, the magnitude 0.0 planet stands 6° high 45 minutes after sundown.

The starry sky

The southern half of the celestial sphere holds several outstanding open star clusters. Although several of my favorites reside in Carina the Keel, this month I want to spend some time with the showpiece of Crux the Cross: the Jewel Box Cluster (NGC 4755). During May, this distinctive constellation climbs highest in the south in midevening.

The Jewel Box lies just 1° southeast of the magnitude 1.3 star Beta (β) Crucis. Although the cluster looks like a fuzzy star to the naked eye, binoculars reveal its true nature. The view through a telescope, however, is the one you won't soon forget. NGC 4755 looks a bit like an arrowhead, but I find it more closely resembles an uppercase letter A. The cluster's brightest star is magnitude 5.8 SAO 252069, which marks the top of the A. Kappa (κ) Cru is 0.1 magnitude fainter and lies at the A's bottom right.

But perhaps the cluster's most outstanding feature is the presence of a distinctly orange-red star in the A's crossbar. This magnitude 7.5 sun, cataloged as SAO 252073, is a red supergiant swimming in a sea of mostly blue giants and supergiants.

The Jewel Box got its name from English astronomer John Herschel — son of William, who discovered Uranus — when he observed the cluster from South Africa in the 19th century. He wrote that the colors of its stars "give it the effect of a superb piece of jewellery." And he called SAO 252073, "The central star (extremely red) of a most vivid and beautiful cluster of from 50 to 100 stars."

Astronomers estimate NGC 4755 lies between 6,500 and 7,800 light-years from Earth. (Its distance is difficult to pinpoint because the Coalsack Nebula lies nearby and obscures some of its light.) Compare this to the Southern Pleiades (IC 2602) in Carina, which lies only 550 light-years away. If the Jewel Box were at this distance, the combined light of its stars would match Sirius, and the cluster would spread across more than 2° of sky!

STAR DOME

HOW TO USE THIS MAP

This map portrays the sky as seen near 30° south latitude. Located inside the border are the cardinal directions and their intermediate points. To find stars, hold the map overhead and orient it so one of the labels matches the direction you're facing. The stars above the map's horizon now match what's in the sky.

The all-sky map shows how the sky looks at:

9 P.M. May 1
8 P.M. May 15
7 P.M. May 31

Planets are shown at midmonth

MAP SYMBOLS

- Open cluster
- Globular cluster
- Diffuse nebula
- Planetary nebula
- Galaxy

STAR MAGNITUDES

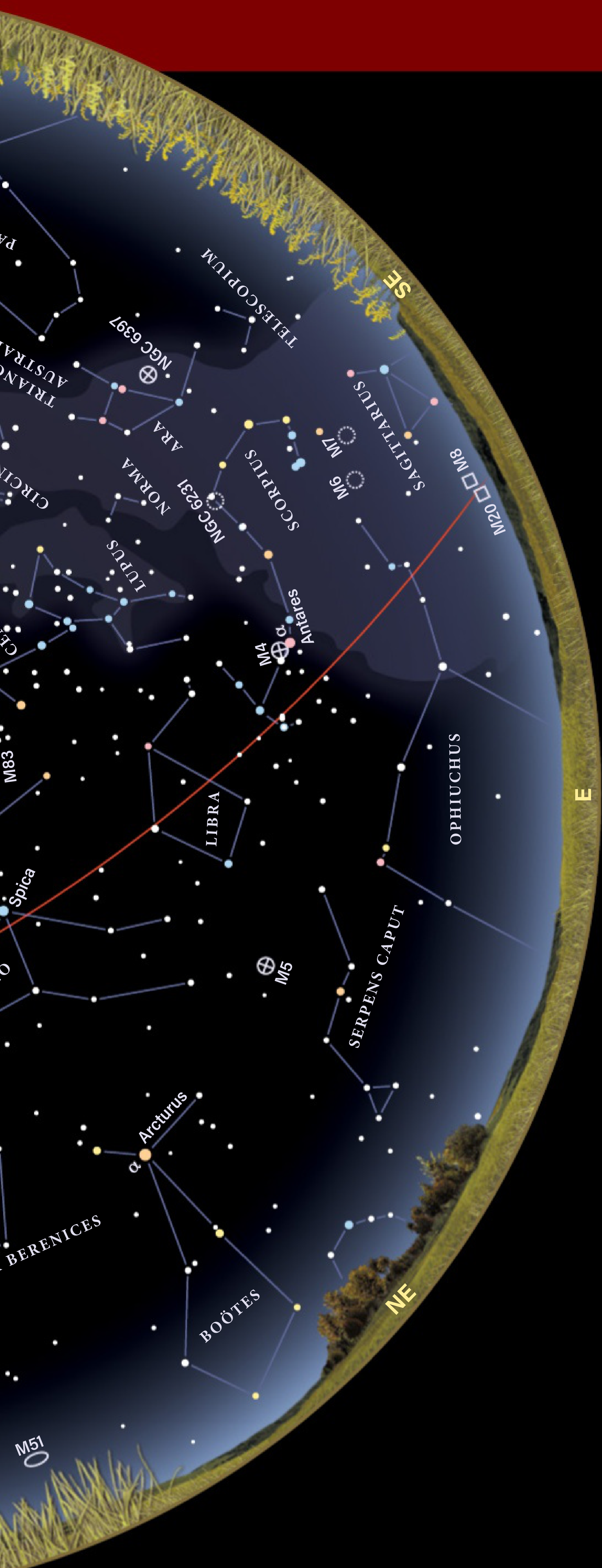
- Sirius
- 0.0
- 1.0
- 2.0
- 3.0
- 4.0
- 5.0

STAR COLORS

A star's color depends on its surface temperature.

- The hottest stars shine blue
- Slightly cooler stars appear white
- Intermediate stars (like the Sun) glow yellow
- Lower-temperature stars appear orange
- The coolest stars glow red
- Fainter stars can't excite our eyes' color receptors, so they appear white unless you use optical aid to gather more light

BEGINNERS: WATCH A VIDEO ABOUT HOW TO READ A STAR CHART AT **www.Astronomy.com/starchart.**



MAY 2020

SUN.	MON.	TUES.	WED.	THURS.	FRI.	SAT.
					1	2
3	4	5	6	7	8	9
10	11	12	13	14	15	16
17	18	19	20	21	22	23
24	25	26	27	28	29	30
31						

ILLUSTRATIONS BY *ASTRONOMY*: ROEN KELLY

Note: Moon phases in the calendar vary in size due to the distance from Earth and are shown at 0h Universal Time.

CALENDAR OF EVENTS

4 Mercury is in superior conjunction, 22h UT

6 The Moon is at perigee (359,654 kilometers from Earth), 3h03m UT

7 Full Moon occurs at 10h45m UT

11 Saturn is stationary, 9h UT

Asteroid Pallas is stationary, 11h UT

12 The Moon passes 2° south of Jupiter, 10h UT

The Moon passes 3° south of Saturn, 18h UT

13 Venus is stationary, 10h UT

14 Last Quarter Moon occurs at 14h03m UT

Jupiter is stationary, 18h UT

15 The Moon passes 3° south of Mars, 2h UT

16 The Moon passes 4° south of Neptune, 15h UT

17 Mercury passes 7° north of Aldebaran, 9h UT

18 The Moon is at apogee (405,583 kilometers from Earth), 7h45m UT

20 The Moon passes 4° south of Uranus, 16h UT

22 Mercury passes 0.9° south of Venus, 8h UT

New Moon occurs at 17h39m UT

24 The Moon passes 4° south of Venus, 3h UT

The Moon passes 3° south of Mercury, 11h UT

The Moon passes 0.6° north of asteroid Vesta, 15h UT

27 Asteroid Juno is stationary, 14h UT

30 First Quarter Moon occurs at 3h30m UT